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Distance Perception in an Optical Tunnel: An Ecological Perspective

Seokhun Kim
seok.kim@uconn.edu

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Distance Perception in an Optical Tunnel: An Ecological Perspective

Seokhun Kim, PhD.

University of Connecticut, 2017

An optical tunnel, a device that allows manipulation of surface layout in which to-be-perceived targets can be embedded, was used to examine distance perception against the backdrop of predictions from two influential computational approaches. Contrary to expectations of the *ground dominance hypothesis*, Experiment 1 showed that objects on the ground surface were not perceived more accurately than objects attached to the ceiling. Contrary to expectations from the *sequential surface integration process hypothesis (SSIP)*, Experiment 2 showed that the reliability of distance perception did not differ whether the surface density was continuous or discontinuous and that, for continuous density, reliability did not differ whether it was dense or sparse. Also contrary to *SSIP*, Experiment 3 showed that manipulation of the surface layout beyond the range of sequential integration mattered to the accuracy of distance perception. Results were discussed within an ecological reframing of the problem of distance perception. To the extent that perception is dependent on detecting an optical invariant, global surface layout should matter and distance perception should not be procedurally different for differences in discontinuity or density. Recasting the notion of distance perception in terms of *affordances*, behavioral possibilities of objects and surfaces, will provide constraints on identifying the relevant optical invariants.

Distance Perception in an Optical Tunnel: An Ecological Perspective

Seokhun Kim

B.S., Seoul National University, 2006

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APPROVAL PAGE

Doctor of Philosophy Dissertation

Distance Perception in an Optical Tunnel: An Ecological Perspective

Presented by

Seokhun Kim, B.S.

Major Advisor_____Till D. Frank

Associate Advisor_____Claudia Carello

Associate Advisor_____Steven J. Harrison

University of Connecticut

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Chapter 1: Introduction

Space Perception and Optical Tunnel

The problem of space perception has fascinated philosophers, mathematicians, and artists for centuries (Boring, 1942; Pastore, 1971). Psychologists engaged in the experimental investigation of space perception confront the challenge of how best to control stimulation. They often opt for two-dimensional displays, either pictures or computer simulations, in order to achieve systematic control of presented structure. During the middle of the last century, James Gibson provided a method that allows systematic manipulation of three-dimensional surface structure: the *optical tunnel* (Figure 1). Despite the fact that “It enables *E* to produce synthetic perceptions of space so as to test hypotheses about the natural perception of space” (Gibson, Purdy, & Lawrence, 1955, p. 10), it has been used minimally. Gibson and his students used it to assess conditions that allow one to see a solid surface of a definite extent and slant (Beck, 1960; Gibson et al., 1955). In particular, they investigated perception of the tunnel itself. More recently, the potential of the tunnel to provide embedding structure was exploited in order to examine perception of objects presented within the tunnel (Kim, Carello, & Turvey, 2016) and that provides the focus of the present dissertation.

< Figure 1 About Here >

The ultimate goal of the dissertation is to contribute to an understanding of the optical structure specific to perceived distance. To that end, the present experiments examine the influence of texture density and continuity, both of which have been shown to be relevant in previous tunnel experiments. In order to further delimit the exploratory nature of the manipulations, given that the potential of the optical tunnel is just beginning to be tapped, the present experiments are designed against the backdrop of predictions from a particular

computational model that was motivated by Gibson's (1950) characterization of visual space in terms of what he called the *ground theory*.

Ground Theory

In distinguishing ground theory from the more orthodox "air theory," Gibson (1950) proposed that visual space be conceptualized as an array of adjoining surfaces rather than an empty coordinate system. In particular, he emphasized the importance of a continuous background surface with stochastically regular structure (i.e., a texture gradient) for spatial perception. A large number of studies have revealed what appears to be a unique role of the ground surface in 3D visual perception (e.g., Bian & Andersen, 2010, 2011; Bian, Braunstein, & Andersen, 2005, 2006; Feria, Braunstein, & Andersen, 2003; Sinai, Ooi, & He, 1998; Wu, Ooi, & He, 2004; Wu, Zhou, Shi, He, & Ooi, 2015). However, the interpretation of the ground theory in those studies has deviated from the ecological direction taken by Gibson's later works.

Gibson (1966, 1979/1986) developed the ground theory into an ecological theory of invariant structures of the ambient optic array. The ambient optic array at a point of observation is structured light of different intensities in different directions, which is lawfully generated by the environmental surface layout and, perforce, specific to that layout (Gibson, 1966, 1979/1986). As the point of observation moves, the nested hierarchy of optical solid angles lawfully transforms leaving invariant optical relations specifying the propertyed relational structures of the environmental surface layout (Kim et al., 2016). Visual perception of environmental properties such as distance is directly tied to these optical invariants in the optic array. In the ecological perspective, the texture gradient of a ground plane, for example, is not a cue for further internal computation but an invariant of optical structure detected in spatial perception.

In contrast, studies of the so-called “ground dominance effect” (Bian et al., 2005) have interpreted the unique role of the ground surface as the result of an internal cue processing framework. The visual system is said to encode the ground plane more efficiently and more accurately (Bian & Andersen, 2011) than other surfaces, presumably due to an evolutionary adaptation to this common surface, allowing it to be used as a reference frame for encoding object locations. In this computational framework, the texture gradient is one of the depth cues used to establish the representation of a ground surface.

An influential theory for the construction of a ground representation is the *sequential surface integration process* (SSIP) hypothesis (He, Wu, Ooi, Yarbrough, & Wu, 2004; Wu et al., 2004). It proposes that processing (1) begins to represent the near ($< 2 - 3$ m) ground surface (He et al., 2004; Loomis, Silva, Philbeck, & Fukusima, 1996; Wu et al., 2004) accurately with reliable near depth cues (e.g., accommodation, binocular disparity, motion parallax) and (2) uses this accurate near-ground representation as a foundation to sequentially integrate farther ground surfaces in the intermediate distance range, based on their texture gradients as a depth cue. A texture discontinuity (i.e., an abrupt change in texture density) in a ground plane would interrupt the smooth integration of the continuous ground surface, requiring the visual system to restart its integration from the boundary. In such a situation, a kind of “discontinuity effect” (Bian et al., 2006) would be expected due to the absence of an accurate anchoring surface (i.e., near-ground surface), resulting in inaccurate, underestimated distance perception (He et al., 2004; Sinai et al., 1998).

In the present study, an optical tunnel is used to systematically manipulate texture properties (i.e., texture density and continuity) of structured surface layout. In ecological parlance, the tunnel’s alternating rings generate an optic array of a nested hierarchy of optical

solid angles; gradients and discontinuities in optical texture are information for the visual perception of surface layout. A higher-order optical structure invariant over this optical texture is expected to be a determinant of distance perception. In consequence, distance perception should be influenced not only by computationally obvious visual cues but also non-obvious optical variables generated by the given surface layout (see also Kim et al., 2016). While early tunnel experiments demonstrated that the nested contact relations (cf. Meng & Sedgwick, 2001, 2002) among these concentric rings provide the impression of a solid tunnel for observers (Beck, 1960; Gibson et al., 1955), the present experiments address whether they also provide a basis for perceiving the distance of objects embedded in the tunnel.

Overview of the Experiments

As noted, despite the potential of the optical tunnel for systematic investigation of so-called space perception—a domain that has held long-standing importance to general theories of perception—this potential was untapped for 60 years. Research questions in this nascent effort can be circumscribed by issues that speak directly to alternative accounts of ground-based space perception. In particular, manipulations motivated by SSIP predictions provide a backdrop against which to search for an optical invariant for distance perception on a structured surface layout. The optical tunnel provides a means to structure 3D surface layout equally all around (above and below the target as well as to the sides), providing a useful foundation for investigating effects of surface layout on distance perception while minimizing the kinds of confounding variables typical of 2D displays. Specifically, it could provide an appropriate ground to test the SSIP's logic of integration of texture gradient cues along the given surface layout, or the ecological theory's notion of specifying optical invariant (for distance) in the optical gradient from the surface layout. Confronting the primacy of the ground surface directly,

Experiment 1 evaluates distance perception for targets attached to the ground or to the ceiling of the tunnel in order to contrast the ground dominance effect with the possibility of specific optical structure. Subsequent experiments are limited to distance perception along the structured tunnel ground. The discontinuity effect is considered in Experiment 2, contrasting the putative disruption of integration with the possibility of distinct optical invariants. The contribution of surface layout posterior to the target is examined in Experiment 3 to evaluate whether optical structure beyond the range of sequential integration matters to distance perception.

General Methodology

Apparatus and materials. The optical tunnel employed here (Figure 2) allowed a maximum of 80 alternating black and white, $40\text{ cm} \times 40\text{ cm} \times 1\text{ mm}$ metal sheets each of which had a centered 30 cm diameter hole. The separation between sheets could be varied, with a minimum of 1 cm. The entire tunnel length, L , was 400 cm; when the 80 sheets were uniformly distributed, the separation between sheets was 5 cm. The tunnel rested on a $410\text{ cm} \times 70\text{ cm}$ wooden table 95 cm above the floor. At the proximal end of the tunnel, a black sheet with a centered 5 cm diameter hole allowed monocular observation. An adjustable chinrest was placed in front of the observation hole to put the observer's dominant eye at the center of the tunnel's concentric rings. At the terminus of the tunnel, a solid white sheet occluded the area behind the tunnel. Two $200\text{ cm} \times 3\text{ cm}$ LED light bars were connected in series and positioned 10 cm above the top of the sheets for uniform illumination of the surface layout.

< Figure 2 About Here >

The target object was a $5\text{ cm} \times 5\text{ cm}$ yellow square cardstock which could be attached to any concentric ring. The position of the target could be changed from the ground to the sides or

the ceiling by rotating the sheet. The location of the target could be anywhere in the tunnel by replacing the original tunnel sheet at that location with the sheet with the target.

For magnitude production trials (Experiments 2 and 3), a distance-reporting instrument was constructed from a string-and-pulley system with a movable 20 cm height stanchion on a 420 cm \times 7 cm \times 7 cm rail, affixed to the right of and parallel to the tunnel at the height of 95 cm (Figure 2). The distance marker, a 6.5 cm diameter black hexagon, could be attached frontally on the stanchion at any height; participants could position the marker (and the stanchion) along the rail by rotating the handle of the pulley at the start point of the rail.

Procedure. At the beginning of an experiment, ocular dominance was determined via the Miles test (Miles, 1930). The chinrest was adjusted to center the seated participant's dominant eye at the center of the tunnel. Each participant was instructed to place his or her jaw on the support and view the target in the tunnel monocularly with the dominant eye. For magnitude estimation tasks (Experiments 1A and 1B), the participant provided a verbal estimate of the target distance in feet and inches or meters and centimeters (cf. Gibson et al., 1955). For magnitude production tasks (Experiments 2-3), the participant was allowed to look back and forth between the target and the response device, while aligning the distance marker with the target location in the tunnel as precisely as possible. Between trials, a curtain (107 cm \times 160 cm) was lowered to occlude the tunnel and the experimenter's adjustments from the participant. The participants were asked not to use any explicit strategies. For example, they were instructed not to (1) count the number of alternating black and white rings, (2) guess the ratio of the target location to the total length of the tunnel, (3) judge distance from the end of the tunnel, (4) infer distance from the size of the target or, specifically in the case of magnitude production, (5) match target and distance marker sizes. They were instructed to focus only on the target and either

estimate its distance (for magnitude estimation tasks), or match its location (for magnitude production tasks). This instruction was repeated every six trials to prevent participants from initiating an explicit strategy. They were debriefed after the study to ensure that no analytic strategy had been used. None were uncovered.

Dependent variables and analyses. Whether magnitude estimation or magnitude production, a measure of perceived distance was obtained on every trial. Observers' reliability and accuracy in judging target distance were assessed by procedures common for perception of magnitudes (e.g., Norman, Todd, Perotti, & Tittle, 1996): Average Deviation, *AD*, was used as a measure of reliability, and Mean-root-square error, *MRS_{error}*, was used as a measure of accuracy.

AD is the mean absolute deviation expressed as a percentage of $\langle D' \rangle$, the mean perceived distance of the trials for a specific combination of target distance and target position, density, or discontinuity, thereby providing a normalized measure of the consistency or reliability of a participant's responses:

$$AD\% = \frac{(\sum |D'_i - \langle D' \rangle|) / n}{\langle D' \rangle} \times 100$$

where *i* signifies each individual trial of *n* repetitions (*n* = 5 for Experiments 1 and 2; *n* = 4 for Experiment 3). A higher value indicates less consistency (more variability). Averaged across the distances, for example, mean *AD*% yields the reliability measure for a specific target condition, and reliability for different target conditions can be compared.

MRS_{error}, referred to as mean-root-square error, provides a comparable accuracy measure, scaled as a percentage of actual distance (see also Carello, Kinsella-Shaw, Amazeen, & Turvey, 2006). This reveals how much one's perceived distance *D'* varies from the actual distance *D*, being calculated as a percentage of *D*. A higher value indicates less accuracy. The percentage *MRS_{error}* for *D'* is calculated according to the following equation:

$$MRS\% = \frac{(\sum \sqrt{(D'_i - D)^2})/n}{D} \times 100$$

where i signifies each individual trial of n repetitions. It should be noted that MRS_{error} is linearly correlated with the more standard RMS_{error} in which the deviations of perceived from actual are summed prior to taking the root. The benefit of MRS_{error} is that it scales the error as a dimensionless Weber fraction, thus functioning like the reliability measure (Carello et al., 2006). Whereas AD captures random error, MRS_{error} captures systematic error. If $AD = MRS_{error}$, then actual distance is the only influence on perceived distance. Differences between AD and MRS_{error} are helpful in identifying systematic influences on perceived distance.

Chapter 2: Re-examining the Ground Dominance Effect

Experiment 1A

In the perspective of the ecological approach, the ostensible ground dominance effect should be information-based (a structural difference between different surfaces) rather than processing-based (an intrinsic mechanism for coding efficiency; Bian et al., 2005, 2006). Experiments that demonstrate ground dominance typically use computer simulations with a simple forced choice task: Which of two targets is farther (e.g., Bian et al., 2005, 2006). An intended 3D demonstration (Bian et al., 2005) did not control the structure generated by floor, walls, and ceiling. In the present study, the optical tunnel was used to provide an equally structured 3D surface layout for the ground, ceiling, and walls. In addition, the target (5 cm × 5 cm yellow cardstock) was placed at different locations within the tunnel's length L , with a numerical verbal response collected for each. Using the chinrest to center the observation point relative to the ground and ceiling of the tunnel controlled eye height and angular declination for different surfaces (Ooi, Wu, & He, 2001; Sedgwick, 1983). If the ground dominance effect is anchored in a visual system bias, perceived distance should be more accurate for ground-mounted targets than for ceiling-mounted targets (Bian & Andersen, 2011). If, in contrast, the ground dominance effect is due to differences in optical structure, there should be no difference in the accuracy of perceived distance between ground- and ceiling-mounted targets because the optical structure is the same.

Method

Participants. Twenty students (6 male and 14 female) at the University of Connecticut participated in partial fulfillment of a course requirement. Ages ranged from 18 to 24 years. Eighteen individuals were right-eye dominant; two were left-eye dominant. The Institutional

Review Board (IRB) of the university approved all experimental procedures. Oral informed consent was obtained from each participant at the start of the experiment.

Design and procedure. Experiment 1A was a 2 Target position (Ground, Ceiling) \times 3 Target location (145, 250, and 355 cm from the observation point, corresponding approximately¹ to .375L, .625L, and .875L) within-subject design with 5 repetitions of each combination (Figure 3a-b). The total 30 trials were completely randomized across participants. Target distance was reported via magnitude estimation: Participants provided a verbal estimate of target distance using their preferred measuring system, imperial (i.e., feet and inches) or metric (i.e., meters and centimeters), while viewing the target in the tunnel. At the beginning of the experiment, a 3-feet (91.5 cm) ruler was presented to remind the participant how long each unit is. The data reported in feet and inches were converted to metric units after the experiment. The purpose of the magnitude estimation was to avoid any ground bias from looking at the reporting instrument or the room outside the tunnel.

< Figure 3a-d About Here >

Results

Mean perceived distances (D') with standard deviations are shown in Table 1. A 2 (Target position) \times 3 (Target location) repeated measures ANOVA on D' confirmed that D' increased with increases in D , $F(1.05, 19.93) = 65.70$, $p < .001$, $\eta_p^2 = .776^2$. With respect to the target position, D' was significantly larger for the ceiling-mounted targets ($M = 248.79$, $SE = 24.70$) than for the ground-mounted targets ($M = 230.91$, $SE = 22.43$), $F(1, 19) = 19.58$, $p < .001$, $\eta_p^2 = .508$. The Position \times Location interaction was also significant, $F(2, 38) = 4.77$, $p = .014$, η_p^2

¹ The sparse density condition (see *Experiment 2* for details) does not have apertures at .375L = 150 cm or .825L = 350 cm so the closest slots were used.

² The Huynh-Feldt correction for degrees of freedom in a repeated measures ANOVA was applied whenever the sphericity assumption was violated from Mauchly's sphericity test.

= .201. Post-hoc pairwise comparisons for target position with Bonferroni correction showed that D' of the ceiling-mounted target was not significantly larger than D' of the ground-mounted target at .375L, $t(19) = 2.23$, $p = .114$, but was significantly larger at .625L, $t(19) = 4.65$, $p < .001$, and at .875L, $t(19) = 2.76$, $p = .037$.

< Table 1 About Here >

Means of MRS_{error} (the accuracy measure capturing systematic error) are shown in Figure 4a. A 2 (Target position) \times 3 (Target location) repeated measures ANOVA on MRS_{error} revealed that MRS_{error} did not significantly increase with increases in D , $F(1.17, 22.16) = 1.58$, $p = .225$, $\eta_p^2 = .077$: Means were 32.40 ($SE = 4.32$) at .375L, 36.35 ($SE = 4.76$) at .625L, and 42.00 ($SE = 5.98$) at .875L. Also, regarding the target position, MRS_{error} was not significantly different for the ceiling-mounted targets ($M = 37.83$, $SE = 4.27$) than for the ground-mounted targets ($M = 36.00$, $SE = 3.91$), $F(1, 19) = .89$, $p = .359$, $\eta_p^2 = .044$. The Position \times Location interaction was not significant either, $F(2, 38) = 1.10$, $p = .343$, $\eta_p^2 = .055$.

< Figure 4a-b About Here >

Figure 4b presents the results of AD , the reliability measure capturing random error. A 2 (Target position) \times 3 (Target location) repeated measures ANOVA on AD showed that AD did not differ among the target locations, $F(1.51, 28.62) = 2.48$, $p = .114$, $\eta_p^2 = .115$; Means were 13.41 ($SE = 1.23$) at .375L, 11.00 ($SE = 1.01$) at .625L, and 10.91 ($SE = 1.33$) at .875L. Also, AD did not differ between the target positions, $F(1, 19) = .47$, $p = .503$, $\eta_p^2 = .024$; Means were 11.50 ($SE = .99$) for the ceiling-mounted targets, and 12.04 ($SE = 1.05$) for the ground-mounted targets. The Position \times Location interaction was not significant either, $F(2, 38) = .67$, $p = .519$, $\eta_p^2 = .034$.

To examine differences between systematic error and random error, a 2 (Measure: MRS_{error} , AD) \times 2 (Target position) ANOVA was conducted: The magnitude of error for each combination was averaged across the three target locations. MRS_{error} ($M = 36.92$, $SE = 3.98$) was significantly larger than AD ($M = 11.77$, $SE = .94$), $F(1, 19) = 45.82$, $p < .001$, $\eta_p^2 = .707$. The effect of target position was not significant, $F(1, 19) = .34$, $p = .568$, $\eta_p^2 = .017$. The Measure \times Position interaction was not significant either, $F(1, 19) = 1.44$, $p = .244$, $\eta_p^2 = .071$.

Discussion

Experiment 1A aimed to test the ground dominance effect in the optical tunnel. In contrast to previous studies (e.g., Bian et al., 2005, 2006), the optical tunnel provided an equally structured real 3D surface layout for the ground and ceiling targets. Further, eye height and angular declination were controlled for the ground and ceiling targets. If the ground dominance effect is due to a computational advantage of a ground surface (Bian & Andersen, 2010), D' of the ground-mounted targets should be more accurate than D' of the ceiling-mounted targets; if differences in optical structure generate the ground dominance effect, D' should be indifferent to ceiling or ground attachment in the optical tunnel.

Although the analyses revealed that D' for the ceiling-mounted targets was larger than D' for the ground-mounted targets in the intermediate distance range (i.e., at .625L and .875L), this was not a difference in accuracy: The analysis of MRS_{error} revealed that the accuracy of D' did not differ between the two target positions. This discrepancy is due to inconsistency among the participants: For the .625L target, 13 of the participants underestimated D , but 7 overestimated; for the .875L target, 10 of the participants underestimated D , but 10 overestimated. The underestimations were more severe for the ground-mounted targets, but the overestimations were more severe for the ceiling-mounted targets, thereby resulting in larger average D' for the

ceiling-mounted targets but no difference in accuracy. Due to these overestimations and underestimations, the systematic error was larger than the random error. However, given the possibility that the verbal estimates were influenced by the observers' post-perceptual biases (e.g., Hutchison & Loomis, 2006), it is hard to draw a firm conclusion at this point based on the difference between the two error types.

The lack of a difference in accuracy may suggest that there is no ground dominance effect in the optical tunnel. This point is further supported by the finding that AD did not differ between the target positions. In brief, distance perception was neither more accurate nor more reliable along the ground surface layout when the optical structure is the same along the upper surface, implying that the ground dominance effect may be information-based rather than processing-based. However, the finding of larger D' for the ceiling surface layout deserves comment. As a straightforward result, it is contrary to Bian and Andersen's (2011) finding that D' was more compressed on a ceiling surface. But it may speak to a deeper theoretical point. From an ecological perspective, distance *per se* is not a property that is perceived. It is, instead, a placeholder for functional properties that Gibson (1979/1986) labeled *affordances*. In the present case, we might speculate that the affordances of an object attached to the ceiling differ from those of an object attached to the floor—for example, whether or not a target is reachable or how easily it might be reached (e.g., Carello, Groszofsky, Reichel, Solomon, & Turvey, 1989). Before considering this speculation, an additional control of the optical structure will be implemented in order to confirm the absence of a ground dominance effect.

Experiment 1B

It is noteworthy that, in Experiment 1A, even when the target was attached to the ceiling, the ground surface was visible; similarly, when the target was attached to the ground, the ceiling

surface was visible. To exclude the potential influence of the other visible surface, as suggested by Thompson, Dilda, and Creem-Regehr (2007), the viewing aperture at the observation point was partially blocked to occlude either the ground or the ceiling as appropriate in Experiment 1B. Half of the hole from the top was blocked when the target was located on the ground and half from the bottom was blocked when the target was on the ceiling (Figure 3c-d). The predictions are the same as in Experiment 1A: The ground dominance effect hypothesis (Bian et al., 2005, 2006) predicts that D' should be more accurate for ground-mounted targets than for ceiling-mounted targets due to the visual system's intrinsic bias (Bian and Andersen, 2011).

Method

Participants. Twenty students (8 male and 12 female) at the University of Connecticut participated in partial fulfillment of a course requirement. Ages ranged from 18 to 22 years. Sixteen of them were right-eye dominant and four were left-eye dominant. The Institutional Review Board (IRB) of the university approved all experimental procedures. Oral informed consent was obtained from each participant at the start of the experiment.

Design and procedure. The same 2 Target position (Ground, Ceiling) \times 3 Target location (.375L, .625L, and .875L) within-subject design with 5 repetitions and complete randomization, and the same magnitude estimation procedure (i.e., verbal estimate of target distance) as in Experiment 1A were used in Experiment 1B.

Results

Means of D' with standard deviations are shown in Table 2. A 2 (Target position) \times 3 (Target location) repeated measures ANOVA on D' demonstrated that D' increased with D , $F(1.08, 20.58) = 129.56, p < .001, \eta_p^2 = .872$. With regard to the target position, D' was significantly larger for the ceiling-mounted targets ($M = 184.14, SE = 13.82$) than for the ground-

mounted targets ($M = 171.93$, $SE = 12.27$), $F(1, 19) = 27.67$, $p < .001$, $\eta_p^2 = .593$. The Position \times Location interaction was significant as well, $F(2, 38) = 10.89$, $p < .001$, $\eta_p^2 = .364$. Post-hoc pairwise comparisons for target position with Bonferroni correction showed that D' of the ceiling-mounted target was not significantly larger than D' of the ground-mounted target at .375L, $t(19) = 1.86$, $p = .233$, but was significantly larger at .625L, $t(19) = 7.22$, $p < .001$, and at .875L, $t(19) = 3.74$, $p = .004$. This pattern of significant target position effects is consistent with Experiment 1A.

< Table 2 About Here >

Means of MRS_{error} are shown in Figure 5a. A 2 (Target position) \times 3 (Target location) repeated measures ANOVA on MRS_{error} confirmed that MRS_{error} decreased with increases in D , $F(1.64, 31.16) = 14.81$, $p < .001$, $\eta_p^2 = .438$: Means were 42.86 ($SE = 4.29$) at .375L, 33.50 ($SE = 4.30$) at .625L, and 28.76 ($SE = 4.15$) at .875L. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that MRS_{error} at .625L ($M = 33.50$, $SE = 4.30$) was significantly smaller than MRS_{error} at .375L ($M = 42.86$, $SE = 4.29$), $t(19) = 3.55$, $p = .006$, but MRS_{error} at .875L ($M = 28.76$, $SE = 4.15$) was only marginally smaller than MRS_{error} at .625L, $t(19) = 2.49$, $p = .067$. With respect to the target position, MRS_{error} was significantly smaller for the ceiling-mounted targets ($M = 34.12$, $SE = 3.86$) than for the ground-mounted targets ($M = 35.96$, $SE = 4.10$), $F(1, 19) = 6.08$, $p = .023$, $\eta_p^2 = .242$. The Position \times Location interaction was only marginally significant, $F(2, 38) = 2.77$, $p = .075$, $\eta_p^2 = .127$.

< Figure 5a-b About Here >

Figure 5b presents the results of AD . A 2 (Target position) \times 3 (Target location) repeated measures ANOVA on AD showed that AD did not differ between the target positions, $F(1, 19) = .44$, $p = .513$, $\eta_p^2 = .023$; Means were 9.32 ($SE = 1.07$) for the ceiling-mounted targets, and

9.99 ($SE = .83$) for the ground-mounted targets. The Position \times Location interaction was not significant either, $F(2, 38) = .38, p = .689, \eta_p^2 = .019$. However, AD was significantly different among target locations, $F(1.44, 27.38) = 5.94, p = .013, \eta_p^2 = .238$; Means were 11.77 ($SE = 1.39$) at .375L, 9.72 ($SE = .89$) at .625L, and 7.48 ($SE = .91$) at .875L. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that AD at .875L was significantly smaller than AD at .625L, $t(19) = 3.18, p = .015$, and also than AD at .375L, $t(19) = 2.99, p = .022$, but the latter two did not significantly differ from each other, $t(19) = 1.41, p = .521$.

To examine differences between systematic error and random error, a 2 (Measure: MRS_{error}, AD) \times 2 (Target position) ANOVA was conducted on the magnitude of error, averaged across the three target locations. MRS_{error} ($M = 35.04, SE = 3.96$) was significantly larger than AD ($M = 9.66, SE = .82$), $F(1, 19) = 52.10, p < .001, \eta_p^2 = .733$. Also, the error-magnitude for the ceiling-mounted targets ($M = 21.72, SE = 2.28$) was significantly smaller than that for the ground-mounted targets ($M = 22.98, SE = 2.27$), $F(1, 19) = 5.23, p = .034, \eta_p^2 = .216$, consistent with the respective trends in MRS_{error} and AD . The Measure \times Position interaction was not significant, $F(1, 19) = .690, p = .416, \eta_p^2 = .035$.

Discussion

Experiment 1B aimed to confirm the results of Experiment 1A in a setting with an additional control of optical structure: The viewing aperture was half-blocked to occlude either the ground or the ceiling as appropriate. If the ground dominance effect is due to a visual system bias (the ground dominance effect hypothesis), D' along the ground surface layout should still be more accurate than D' along the ceiling surface layout. The analysis of D' again showed that D' of the ceiling-mounted targets was larger than D' of the ground-mounted targets in the

intermediate distance range. Moreover, in contrast to Experiment 1A, the analysis of MRS_{error} revealed that D' was more accurate for the ceiling surface layout than for the ground surface layout.

The finding that D' was more accurate along the ceiling surface layout is contrary to the prediction of the ground dominance effect hypothesis that D' should be more accurate along the ground surface. Cue-based computational theories would try to attribute this phenomenon to the inverted retinal image—symmetrically reversed visual field—for the ceiling-mounted target with reference to the ground-mounted target (Higashiyama & Adachi, 2006). The two retinal images share all the depth cues except height in the visual field (Dunn, 1965; Epstein, 1966). Bian et al. (2006), however, showed that height in the visual field had only a minor effect when a background surface was provided as in the present study. Thus, for the ground dominance effect hypothesis, the inverted retinal image for the ceiling-mounted targets should have provoked a less efficient and less accurate visual encoding for the same depth cues including eye height and angular declination (Ooi, Wu, & He, 2001), which should have generated more compressed D' for the ceiling than for the ground (e.g., Bian & Andersen, 2011).

Thompson et al. (2007) showed that D' on a ceiling surface was as accurate as D' on a ground surface in a blind-walking task. But they conceded that there might be systematic biases in ground-based blind walking to ceiling targets. In a visual matching task, Thompson et al. also found that observers placed the floor target at a farther distance than the ceiling target, indicating that D' was more compressed on a ground surface than on a ceiling surface, as in the present study. However, their speculative explanation—that observers might have been matching angular declination which was asymmetrical between the ground and the ceiling targets—hinged on the fact that the point of observation was not centered between the ground and the ceiling. In the

present study, eye height and angular declination were controlled between the target positions, undermining that possibility.

A superficial consideration of the optical structure for the two target positions might consider them to be equivalent and simply reflected. However, previous ecological treatments of optical structure suggest that the two arrangements differ with respect to a fundamental feature of surface layout: the horizon. The optical tunnel with the ceiling targets generates an optical structure above the horizon (Figure 3c), while that with the ground targets generates an optical structure below the horizon (Figure 3d). The horizon specifies the observer's eye level (Sedgwick, 1980, 1983), thereby scaling the layout of surfaces to that observer. But optical structure is not limited to information about location. As noted, these different optical structures may specify different affordances—possibilities for action offered by the environment (Gibson, 1979/1986). In the ecological perspective, the environment is perceived in terms of what an animal can do in the environment (Oudejans, Michaels, Bakker, & Dolné, 1996). In the present study, for example, the ceiling targets could be harder to reach than the ground targets, because reaching needs more movements against gravity for the ceiling targets. The optical structure *above* the horizon (from the ceiling) may provide an optical invariant specifying this harder reach-ability, resulting in larger perceived distance, as compared to the optical structure *below* the horizon (from the ground). However, further research is necessary to support and elaborate this reasoning.

In addition, the analysis of AD showed that the reliability of D' did not differ between the ceiling- and ground-mounted targets, suggesting that distance perception is not more efficient for either of the two surfaces. Also, the fact that MRS_{error} was larger than AD indicates that actual distance is not the only influence on distance perception in the optical tunnel. While verbal

estimates may have been biased by the observers' cognitive processes, structural properties of the optical tunnel's surface layout could have influenced distance perception. Computational theories would adopt the nested contact relations among the concentric rings (Meng & Sedgwick, 2001, 2002), and the reliable near depth cues and a smooth integration process anchored in them (He et al., 2004; Wu et al., 2004), which should result in accurate D' . The ecological perspective, in contrast, would argue that non-obvious optical variables generated by the surface layout affect D' (Kim et al., 2016), which may result in inaccurate D' with D as an artificial (not ecological) criterion. The observed systematic error (i.e., inaccurate D') is consistent with the ecological theory rather than the computational theories.

Chapter 3: Ecological Perspective on the Texture Discontinuity Effect

Experiment 2 is intended to replicate the effect of ground plane discontinuity on perceived distance that has been demonstrated in a natural environment. In one version of the discontinuity effect, observers standing on one surface underestimated perceived distance of a target located on a different surface, as measured by blindfolded walking, whether going from concrete to grass or grass to concrete, especially for farther distances (Sinai et al., 1998). Perceived distance was accurate regardless of texture density as long as that density was continuous. Computational theories label the influence of discontinuity as an error. As noted, for example, a discontinuity interrupts the hypothesized integration process (SSIP). But it also would alter the optical structure that specifies distance, suggesting an ecological take on departures from metrical accuracy.

The two approaches make different predictions about response variability. According to the SSIP hypothesis, distance perception of targets beyond the point of texture discontinuity should be more variable than perception of those same targets on a texturally continuous surface, due to the disrupted computational process. In the ecological theory, however, variability should not differ abruptly because distance perception depends on detecting the invariant optical structure generated by the given surface layout, regardless of whether it is continuous or discontinuous. To evaluate these predictions, the effects of texture discontinuity (Experiments 2A and B) and density (Experiment 2C) were investigated in the optical tunnel. In Experiment 2A, near-space was always dense; far-space was either dense or sparse. In Experiment 2B, near-space was always sparse; far-space was either dense or sparse. In Experiment 3, density was continuous, either dense or sparse.

Experiment 2A

The crucial evaluation is for distance perception in far-space (i.e., beyond the potential texture boundary) with and without a discontinuity. MRS_{error} , a measure of accuracy, was predicted to reveal underestimates for the discontinuous condition as compared for the continuous condition, as expected from the literature. At issue for the two approaches is whether AD , a measure of response variability, also differs. Ecological theory predicts no difference in AD as a function of discontinuity; SSIP predicts an increase in AD for the discontinuous condition.

Method

Participants. Twenty students (4 male and 16 female) at the University of Connecticut participated in partial fulfillment of a course requirement. Ages ranged from 18 to 24 years. Seventeen of them were right-eye dominant and three were left-eye dominant. The Institutional Review Board (IRB) of the university approved all experimental procedures. Oral informed consent was obtained from each participant at the start of the experiment.

Apparatus and materials. In Experiments 2A and 2B, the discontinuity occurred halfway through the tunnel at a physical distance of 2 m from the observation point (i.e., at .5L), distinguishing near-space (“personal space” in Cutting & Vishton, 1995; “near visual space” in Norman, Todd, Perotti, & Tittle, 1996) from far-space (2 to 4 m from the observation point) of the tunnel. The physical density of concentric rings in each of the near- and far-spaces could be manipulated. A 5 cm separation between neighboring sheets was defined as *dense*; a 15 cm separation between neighboring sheets was defined as *sparse*. In Experiment 2A, the two tunnel conditions are shown in Figure 6a: continuous (near-space dense/far-space dense) and discontinuous (near-space dense/far-space sparse).

< Figure 6a-c About Here >

The target (5 cm × 5 cm yellow cardstock) was placed along the tunnel ground at one of the three locations as defined in Experiment 1 (i.e., .375L, .625L, and .875L). The distance marker, a 6.5 cm diameter black hexagon, was attached frontally on the stanchion of the reporting instrument at the same physical height as the target in the tunnel.

Design and procedure. Experiment 2A was a 2 Discontinuity (continuous: dense/dense vs. discontinuous: dense/sparse) × 3 Target location (.375L, .625L, and .875L) within-subject design with 5 repetitions of each combination. The total 30 trials were divided into 10 blocks (2 discontinuity × 5 repetitions), each of which had 3 trials for the 3 target locations: Each block had a single discontinuity condition (i.e., continuous or discontinuous) with each of the three target locations. The order was completely randomized between and within blocks across participants. Target distance was reported via magnitude production: The participants were instructed to align the distance marker on the reporting instrument with the target location in the tunnel while looking back and forth between the target and the marker. The magnitude production apparatus (i.e., the distance-reporting instrument) was started at zero for each trial.

Results

Means of D' with standard deviations are shown in Table 3. A 2 (Discontinuity) × 3 (Target location) repeated measures ANOVA on D' confirmed that D' increased with D , $F(2, 38) = 2739.92$, $p < .001$, $\eta_p^2 = .993$. With respect to the discontinuity manipulation, D' was significantly larger for the continuous condition ($M = 228.46$, $SE = 4.91$) than for discontinuous condition ($M = 222.64$, $SE = 5.56$), $F(1, 19) = 14.60$, $p = .001$, $\eta_p^2 = .435$. The Discontinuity × Location interaction was significant as well, $F(2, 38) = 15.63$, $p < .001$, $\eta_p^2 = .451$. Planned pairwise comparisons for discontinuity with Bonferroni correction revealed that D' of the continuous condition was not significantly larger than D' of the discontinuous condition at .375L,

$t(19) = .33, p = 1.00$, but was significantly larger at .625L, $t(19) = 5.02, p < .001$, and at .875L, $t(19) = 3.75, p = .004$.

< Table 3 About Here >

Figure 7a presents the results of MRS_{error} . A 2 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on MRS_{error} demonstrated that MRS_{error} was significantly different among the target locations, $F(2, 38) = 11.35, p < .001, \eta_p^2 = .374$. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that MRS_{error} at .875L ($M = 8.96, SE = 1.52$) was significantly smaller than MRS_{error} at .625L ($M = 13.02, SE = 2.06$), $t(19) = 4.82, p < .001$, and also than MRS_{error} at .375L ($M = 12.80, SE = 2.24$), $t(19) = 3.35, p = .010$, but there was no difference between the latter two, $t(19) = .25, p = 1.00$. With regard to the discontinuity manipulation, MRS_{error} was significantly smaller for the continuous condition ($M = 10.84, SE = 1.76$) than for the discontinuous condition ($M = 12.35, SE = 2.04$), $F(1, 19) = 6.54, p = .019, \eta_p^2 = .256$. The Discontinuity \times Location interaction was also significant, $F(2, 38) = 7.47, p = .002, \eta_p^2 = .282$. Planned pairwise comparisons for discontinuity with Bonferroni correction further revealed that MRS_{error} of the continuous condition was not significantly smaller than MRS_{error} of the discontinuous condition at .375L, $t(19) = .70, p = 1.00$, but was significantly smaller at .625L, $t(19) = 3.39, p = .009$, and also at .875L, $t(19) = 3.61, p = .005$.

< Figure 7a-b About Here >

Figure 7b illustrates the results of AD . A 2 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on AD showed that AD did not differ for the discontinuity manipulation, $F(1, 19) = .01, p = .946, \eta_p^2 = .000$; Means were 3.47 ($SE = .32$) for the continuous condition, and 3.45 ($SE = .54$) for the discontinuous condition. Planned pairwise comparisons for discontinuity with Bonferroni correction further revealed that there was no significant difference in AD

between the continuous and discontinuous conditions at .375L, $t(19) = .28$, $p = 1.00$, at .625L, $t(19) = .15$, $p = 1.00$, nor at .875L, $t(19) = .42$, $p = 1.00$. The Discontinuity \times Location interaction was not significant either, $F(2, 38) = .26$, $p = .773$, $\eta_p^2 = .013$. However, *AD* significantly differed among the target locations, $F(2, 38) = 15.34$, $p < .001$, $\eta_p^2 = .447$; Means were 4.27 ($SE = .52$) at .375L, 3.50 ($SE = .41$) at .625L, and 2.61 ($SE = .37$) at .875L. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that *AD* at .875L was significantly smaller than *AD* at .625L, $t(19) = 3.67$, $p = .005$, and also than *AD* at .375L, $t(19) = 5.35$, $p < .001$, but the latter two did not significantly differ from each other, $t(19) = 2.27$, $p = .105$.

To examine differences between systematic error and random error, a 2 (Measure: *MRS_{error}*, *AD*) \times 2 (Discontinuity) ANOVA was conducted on the magnitude of error, averaged across the three target locations. *MRS_{error}* ($M = 11.59$, $SE = 1.89$) was significantly larger than *AD* ($M = 3.46$, $SE = .40$), $F(1, 19) = 24.04$, $p < .001$, $\eta_p^2 = .558$. The effect of discontinuity was not significant, $F(1, 19) = 2.79$, $p = .112$, $\eta_p^2 = .128$. The Measure \times Discontinuity interaction was significant, $F(1, 19) = 12.85$, $p = .002$, $\eta_p^2 = .403$, due to the different effects of discontinuity on *MRS_{error}* and *AD* as shown above. Planned pairwise comparisons for measure with Bonferroni correction further showed that *MRS_{error}* was significantly larger than *AD* in the continuous condition, $t(19) = 4.67$, $p < .001$, and also in the discontinuous condition, $t(19) = 5.05$, $p < .001$.

Discussion

Experiment 2A aimed to investigate the effect of texture discontinuity in the optical tunnel. Whereas both theories commonly expected that *MRS_{error}*, the accuracy of *D'*, should reveal more underestimates for the discontinuous optical tunnel, their predictions about *AD*, the

response variability of D' , differed: The ecological theory predicted no difference in AD between the continuous and discontinuous tunnels; the SSIP predicted an increase in AD for the discontinuous tunnel.

The analysis of AD supported the predictions from the ecological theory. The discontinuity manipulation did not affect AD at any of the three location in the near- and far-spaces. The response variability did not differ between the continuous and discontinuous tunnels, suggesting that distance perception is not procedurally different between texturally continuous and discontinuous surfaces. This procedural indifference is dissonant with the SSIP's assertion that an integration process is disrupted for a texture discontinuity. The interrupted computational process without an accurate anchor should have resulted in less reliable distance perception, which was not supported. Instead, this finding accords with the ecological theory's assumption that the visual system detects invariant optical structures generated by the given surface layout. Different surface layouts (e.g., continuous or discontinuous) may generate different optical structures specifying distance, but their detection is not procedurally different, resulting in comparable reliability of distance perception.

The analyses of D' and MRS_{error} showed that D' beyond the discontinuity point was more underestimated (i.e., less accurate) in the discontinuous tunnel than in the continuous tunnel. In near-space, there was no difference in D' and its accuracy between the two tunnel layouts. This finding, commonly predicted from both theories (for different reasons), is also consistent with the results of a previous study in a natural environment (Sinai et al., 1998), indicating the potential of the optical tunnel as an appropriate setting for studying distance perception as natural environments.

Further, the fact that MRS_{error} was larger than AD , both in the continuous tunnel and the discontinuous tunnel, indicates that factors other than D influenced distance perception, namely, structural properties of the optical tunnel's surface layout. In a computational perspective, however, the nested contact relations among the concentric rings (Meng & Sedgwick, 2001, 2002) and a smooth integration process anchored in reliable depth cues (He et al., 2004; Wu et al., 2004) should have produced accurate distance perception at least for the continuous tunnel, but did not; this view cannot account for the observed systematic error in distance perception. In the ecological perspective, in contrast, non-obvious optical variables generated by the optical tunnel's surface layout may have affected distance perception (Kim et al., 2016), apparently giving rise to systematic errors, at least relative to D as an artificial criterion.

An additional finding was that both MRS_{error} and AD at .875L were smaller than those at .375L and at .625L but there was no difference between the latter two, respectively. Distance perception, in dimensionless (percentage) measures, was more accurate and reliable for the farthest target, but did not differ between the other two. This finding is consonant with neither the SSIP, in which D' cannot be more accurate and reliable with a lengthened integration process, nor with the ecological theory, in which the reliability should not abruptly change with D . However, it might be due to an anchoring effect given that the reporting device (420 cm) was only slightly longer than the tunnel (400 cm). A deceleration of magnitude reports at the upper end of an anchored scale, a kind of ceiling effect, is a classic psychophysical finding and may have had incidental effects on MRS_{error} and AD .

In summary, the accuracy of D' was different between the continuous and discontinuous tunnels, but (1) the reliability of D' did not differ, and (2) the observed systematic error was not accountable by a cue-based computational theory such as the SSIP even for the continuous

surface layout. These findings favor a characterization of distance perception as detecting an optical invariant from the given surface layout, rather than integrating depth cues from local surface patches in a particular way (e.g., near-to-far direction in the SSIP).

Experiment 2B

Experiment 2B replicated Experiment 2A but with the opposite density order for the discontinuous condition: near-space sparse/far-space dense. The predictions are the same as in Experiment 2A. Ecological theory predicts no difference in AD between the discontinuous and continuous conditions; SSIP predicts an increase in AD for the discontinuous condition. Both theories predict an increase in MRS_{error} , namely, an increase in underestimation, for the discontinuous condition as shown in the literature.

Method

Participants. Twenty students (5 male and 15 female) at the University of Connecticut participated in partial fulfillment of a course requirement. Ages ranged from 18 to 21 years. Fourteen of them were right-eye dominant and six were left-eye dominant. The Institutional Review Board (IRB) of the university approved all experimental procedures. Oral informed consent was obtained from each participant at the start of the experiment.

Apparatus and materials. Dense and sparse were defined as in Experiment 2A. The discontinuity again occurred at 2 m from the observation point, distinguishing near-space from far-space of the tunnel. The two tunnel conditions are shown in Figure 6b: continuous (near-space sparse/far-space sparse) and discontinuous (near-space sparse/far-space dense). The target, target locations, and distance-reporting instrument were the same as in Experiment 2A.

Design and procedure. The design and procedure were the same as in Experiment 2A.

Results

Means of D' with standard deviations are shown in Table 4. A 2 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on D' confirmed that D' increased with D , $F(1.54, 29.29) = 2724.51$, $p < .001$, $\eta_p^2 = .993$. With regard to the discontinuity manipulation, D' was significantly larger for the continuous condition ($M = 220.49$, $SE = 4.63$) than for the discontinuous condition ($M = 217.04$, $SE = 4.75$), $F(1, 19) = 11.63$, $p = .003$, $\eta_p^2 = .380$. The Discontinuity \times Location interaction was also significant, $F(2, 38) = 3.61$, $p = .037$, $\eta_p^2 = .160$. Planned pairwise comparisons for discontinuity with Bonferroni correction demonstrated that D' of the continuous condition was not significantly larger than D' of the discontinuous condition at .375L, $t(19) = .57$, $p = 1.00$, but was significantly larger at .625L, $t(19) = 2.76$, $p = .037$, and at .875L, $t(19) = 3.00$, $p = .022$.

< Table 4 About Here >

Figure 8a illustrates the results of MRS_{error} . A 2 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on MRS_{error} showed that MRS_{error} was significantly different among the target locations, $F(1.21, 22.94) = 4.91$, $p = .031$, $\eta_p^2 = .205$. Post-hoc pairwise comparisons for target location with Bonferroni correction revealed that MRS_{error} at .875L ($M = 10.89$, $SE = 1.35$) was significantly smaller than MRS_{error} at .625L ($M = 14.37$, $SE = 1.98$), $t(19) = 3.77$, $p = .004$, but was not significantly smaller than MRS_{error} at .375L ($M = 15.19$, $SE = 2.82$), $t(19) = 2.20$, $p = .122$. With respect to the discontinuity manipulation, MRS_{error} was significantly smaller for the continuous condition ($M = 12.91$, $SE = 1.94$) than for the discontinuous condition ($M = 14.05$, $SE = 2.01$), $F(1, 19) = 10.14$, $p = .005$, $\eta_p^2 = .348$. The Discontinuity \times Location interaction was not significant, $F(2, 38) = 1.97$, $p = .153$, $\eta_p^2 = .094$. Planned pairwise comparisons for discontinuity with Bonferroni correction revealed that MRS_{error} of the continuous condition was not significantly smaller than MRS_{error} of the discontinuous condition

at .375L, $t(19) = .51$, $p = 1.00$, but was significantly smaller at .625L, $t(19) = 2.94$, $p = .025$, and also at .875L, $t(19) = 2.71$, $p = .042$.

< Figure 8a-b About Here >

Figure 8b presents the results of *AD*. A 2 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on *AD* showed that *AD* did not differ for the discontinuity manipulation, $F(1, 19) = 1.78$, $p = .198$, $\eta_p^2 = .086$; Means were 4.11 ($SE = .50$) for the continuous condition, and 4.43 ($SE = .39$) for the discontinuous condition. Planned pairwise comparisons for discontinuity with Bonferroni correction further revealed that there was no significant difference in *AD* between the continuous and discontinuous conditions at .375L, $t(19) = .72$, $p = 1.00$, at .625L, $t(19) = 2.55$, $p = .060$, nor at .875L, $t(19) = 1.44$, $p = .497$. The Discontinuity \times Location interaction was only marginally significant, $F(2, 38) = 2.66$, $p = .083$, $\eta_p^2 = .123$. On the other hand, *AD* significantly differed among the target locations, $F(1.47, 27.90) = 7.41$, $p = .005$, $\eta_p^2 = .281$; Means were 5.15 ($SE = .69$) at .375L, 4.52 ($SE = .52$) at .625L, and 3.15 ($SE = .31$) at .875L. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that *AD* at .875L was only marginally smaller than *AD* at .625L, $t(19) = 2.61$, $p = .051$, but significantly smaller than *AD* at .375L, $t(19) = 2.99$, $p = .023$, but the latter two did not significantly differ from each other, $t(19) = 1.78$, $p = .276$.

To examine differences between systematic error and random error, a 2 (Measure: MRS_{error} , *AD*) \times 2 (Discontinuity) ANOVA was conducted on the magnitude of error, averaged across the three target locations. MRS_{error} ($M = 13.48$, $SE = 1.96$) was significantly larger than *AD* ($M = 4.27$, $SE = .43$), $F(1, 19) = 32.49$, $p < .001$, $\eta_p^2 = .631$. The error-magnitude for the discontinuous condition ($M = 9.25$, $SE = 1.17$) was significantly larger than that for the continuous condition ($M = 8.51$, $SE = 1.18$), $F(1, 19) = 9.90$, $p = .005$, $\eta_p^2 = .342$, due to the

significantly larger MRS_{error} and the non-significant but larger AD for the discontinuous condition as shown above. The Measure \times Discontinuity interaction was only marginally significant, $F(1, 19) = 4.17, p = .055, \eta_p^2 = .180$. Planned pairwise comparisons for measure with Bonferroni correction further showed that MRS_{error} was significantly larger than AD in the continuous condition, $t(19) = 5.61, p < .001$, and also in the discontinuous condition, $t(19) = 5.71, p < .001$.

Discussion

Experiment 2B aimed to investigate the effect of texture discontinuity in the opposite density order to Experiment 2A: The near-space was controlled to be sparse, and the far-space was manipulated between dense and sparse. The predictions from the two theories were the same as those in Experiment 2A: an increase in MRS_{error} for the discontinuous tunnel (common); no difference in AD between the discontinuous and continuous tunnels (Ecological theory); an increase in AD for the discontinuous tunnel (SSIP).

As in Experiment 2A, the analyses of AD favored the predictions from the ecological theory. The response variability of D' did not differ between the continuous and discontinuous tunnels at any of the three location in the near- and far-spaces. This finding, again, is dissonant with the SSIP's idea that an integration process is disrupted for a texture discontinuity, but consonant with the ecological theory's view that distance perception depends on detecting the invariant optical structure generated by the given surface layout.

The analyses of D' and MRS_{error} also showed that D' in far-space was less accurate in the discontinuous tunnel layout than in the continuous tunnel layout, as predicted from both theories. Moreover, the systematic error (MRS_{error}) was larger than the random error (AD) both in the continuous tunnel and the discontinuous tunnel, as in Experiment 2A. As explained above, this

observed systematic error, especially for the continuous tunnel layout, is not readily accountable by a cue-processing theory based on the nested contact relations among the concentric rings and a smooth integration process anchored in reliable depth cues. In the ecological perspective, however, the effect of non-obvious optical variables generated by the given surface layout is consistent with this phenomenon.

In addition, similar trends of MRS_{error} and AD on D as in Experiment 2A were found: MRS_{error} was smaller at .875L than at .625L, and AD was smaller at .875L than at .375L, but there was no other significant difference between pairs in spite of the smallest mean MRS_{error} and AD at .875L. As speculated above, the increased accuracy and reliability at .875L might be due to an anchoring effect due to the fixed scale provided by the reporting device.

In summary, D' was less accurate in the discontinuous tunnel layout, but the reliability of D' did not differ between the continuous and discontinuous tunnels, supporting the predictions of the ecological theory. Also, a cue-based theory such as the SSIP could not explain the observed systematic error even for the continuous surface layout. In brief, Experiment 2B confirmed the findings of Experiment 2A with the opposite density order for the discontinuous condition (near-space sparse/far-space dense), suggesting that those findings were not due to a particular density order but due to detection of an optical invariant specifying distance.

Experiment 2C

The results of Experiments 2A and 2B suggest that structural *discontinuity* matters to distance perception. However, the effect of texture density *per se* needs to be clarified. Gibson et al. (1955), for example, showed an effect of texture density on perception of characteristics of the tunnel itself. In particular, the denser the apertures the longer the tunnel appeared.

Experiment 2C is directed at the influence of texture density on distance perception of targets embedded within the tunnel.

The SSIP hypothesis predicts that *AD* will be larger when the surface layout is sparser than when it is denser. Sequential integration should be easier and more efficient when local surface patches of contrasting white and black textures are more closely adjoined (suggesting that, in some sense, denser surface layout is “better” for distance perception, resulting in more consistent performance). From the ecological perspective, in contrast, it might be argued that the global gradient is the same between the dense and the sparse conditions. In the absence of structural discontinuity, therefore, the corresponding prediction is that *AD* should not differ between the two density conditions. But the effect to be expected on *MRS_{error}* is not clear. On the one hand, the sameness of the global gradients suggests that *MRS_{error}* should not differ between the dense and the sparse conditions. On the other hand, the original optical tunnel experiment showed that density mattered to perception of the extent of the tunnel itself—the denser the arrangement, the longer the tunnel appeared (Gibson et al., 1955)—allowing the possibility that the information specifying distance is different. This would be revealed by a difference in *MRS_{error}*.

Method

Participants. Twenty students (8 male and 12 female) at the University of Connecticut participated in partial fulfillment of a course requirement. Ages ranged from 18 to 24 years. Fifteen of them were right-eye dominant and five were left-eye dominant. The Institutional Review Board (IRB) of the university approved all experimental procedures. Oral informed consent was obtained from each participant at the start of the experiment.

Apparatus and materials. In Experiment 2C, the tunnel was either dense or sparse continuously throughout near-space and far-space (Figure 6c). The target, target locations, and the distance-reporting instrument were the same as in Experiments 2A and 2B.

Design and Procedure. The design and procedure of Experiment 2C were the same as in Experiments 2A and B with the exception that density was manipulated (dense throughout vs. sparse throughout) rather than continuity.

Results

Means of D' with standard deviations are shown in Table 5. A 2 (Density) \times 3 (Target location) repeated measures ANOVA on D' confirmed that D' increased with D , $F(1.40, 26.51) = 2435.22$, $p < .001$, $\eta_p^2 = .992$. With regard to the density manipulation, however, there was no significant difference in D' between the dense condition ($M = 231.26$, $SE = 3.26$) and the sparse condition ($M = 231.73$, $SE = 3.91$), $F(1, 19) = .12$, $p = .737$, $\eta_p^2 = .006$. The Density \times Location interaction was not significant either, $F(2, 38) = 2.10$, $p = .137$, $\eta_p^2 = .099$.

< Table 5 About Here >

Figure 9a demonstrates the results of MRS_{error} . A 2 (Density) \times 3 (Target location) repeated measures ANOVA on MRS_{error} showed that MRS_{error} was significantly different among the target locations, $F(2, 38) = 10.99$, $p < .001$, $\eta_p^2 = .366$. Post-hoc pairwise comparisons for target location with Bonferroni correction revealed that MRS_{error} at .875L ($M = 6.46$, $SE = 1.05$) was significantly smaller than MRS_{error} at .625L ($M = 10.69$, $SE = 1.47$), $t(19) = 5.26$, $p < .001$, and also than MRS_{error} at .375L ($M = 10.05$, $SE = 1.49$), $t(19) = 3.02$, $p = .021$, but there was no difference between the latter two, $t(19) = .72$, $p = 1.00$. Regarding the density manipulation, however, MRS_{error} was not significantly different between the dense condition ($M = 8.90$, $SE =$

1.16) and the sparse condition ($M = 9.23$, $SE = 1.33$), $F(1, 19) = .51$, $p = .485$, $\eta_p^2 = .026$. Also, the Density \times Location interaction was not significant, $F(2, 38) = 1.23$, $p = .304$, $\eta_p^2 = .061$.

< Figure 9a-b About Here >

Figure 9b illustrates the results of *AD*. A 2 (Density) \times 3 (Target location) repeated measures ANOVA on *AD* showed that *AD* did not differ for the density manipulation, $F(1, 19) = 1.90$, $p = .184$, $\eta_p^2 = .091$; Means were 3.38 ($SE = .22$) for the dense condition, and 3.13 ($SE = .19$) for the sparse condition. Planned pairwise comparisons for density with Bonferroni correction further showed that there was no significant difference in *AD* between the dense and sparse conditions at .375L, $t(19) = .38$, $p = 1.00$, at .625L, $t(19) = .84$, $p = 1.00$, nor at .875L, $t(19) = 2.23$, $p = .114$. The Density \times Location interaction was not significant either, $F(2, 38) = .62$, $p = .544$, $\eta_p^2 = .032$. However, *AD* significantly differed among the target locations, $F(2, 38) = 5.64$, $p = .007$, $\eta_p^2 = .229$; Means were 3.62 ($SE = .28$) at .375L, 3.51 ($SE = .27$) at .625L, and 2.62 ($SE = .23$) at .875L. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that *AD* at .875L was significantly smaller than *AD* at .625L, $t(19) = 2.66$, $p = .047$, and also than *AD* at .375L, $t(19) = 3.58$, $p = .006$, but the latter two did not significantly differ from each other, $t(19) = .30$, $p = 1.00$.

To examine differences between systematic error and random error, a 2 (Measure: MRS_{error} , *AD*) \times 2 (Density) ANOVA was conducted on the magnitude of error, averaged across the three target locations. MRS_{error} ($M = 9.06$, $SE = 1.23$) was significantly larger than *AD* ($M = 3.25$, $SE = .18$), $F(1, 19) = 23.46$, $p < .001$, $\eta_p^2 = .553$. The effect of density was not significant, $F(1, 19) = .02$, $p = .886$, $\eta_p^2 = .001$. The Measure \times Density interaction was not significant either, $F(1, 19) = 1.90$, $p = .184$, $\eta_p^2 = .091$. Planned pairwise comparisons for measure with Bonferroni

correction further showed that MRS_{error} was significantly larger than AD in the dense condition, $t(19) = 4.83, p < .001$, and also in the sparse condition, $t(19) = 4.73, p < .001$.

Discussion

Experiment 2C aimed to examine the effect of texture density in the optical tunnel. Whereas predictions about MRS_{error} were exploratory, the predictions about AD differed between the two theories: The ecological theory predicted no difference in AD between the dense and sparse tunnels; the SSIP predicted larger AD for the sparse tunnel.

The analysis of AD supported the predictions of the ecological theory. The response variability of D' did not differ between the dense and sparse tunnels at any of the three location in the near- and far-spaces, suggesting that distance perception is not different in procedural efficiency between texturally dense and sparse surface layouts. This finding is inconsistent with the SSIP's assumption that a sequential integration process would be easier and more efficient for more closely adjoined local surface patches in the far-space. In contrast, this finding concurs with the ecological theory's contention that the detection of an invariant optical structure is procedurally indifferent to whether the given surface layout is dense or sparse.

The analyses of D' and MRS_{error} revealed that the accuracy of D' did not differ between the dense and sparse tunnels. This finding could be harmonious with both theories, and thus, does not differentiate them: In the SSIP, the continuous surface layout of either tunnel upholds a smooth integration based on the accurate anchor from the near-space, thus yielding similarly accurate D' ; in the ecological theory, the optical invariant specifying distance might be the same between the dense and sparse surface layouts due to the same global optical gradient and the lack of structural discontinuity.

On the other hand, the systematic error (MRS_{error}) was larger than the random error (AD) both in the dense tunnel and the sparse tunnel. Both tunnels provide a continuous surface layout, and thus for the SSIP, a smooth integration process anchored in reliable depth cues should have resulted in accurate distance perception for both, which was not supported. Instead, as noted above, this finding indicates that perceived distance is influenced by something in addition to distance. In the ecological perspective, this influence is provided by non-obvious optical variables generated by the given surface layout. And once again, the smaller values of MRS_{error} and AD at .875L are likely due to the same kind of anchoring effect seen in Experiment 2A and 2B.

In summary, (1) neither the accuracy nor the reliability of D' differed between the dense and sparse tunnel surface layouts, and (2) the SSIP could not explain the observed systematic error, both favoring the ecological theory's notion of detecting an optical invariant generated by the surface layout. In particular, these results cast doubt on the suggestion that denser surface layout might be "better" for distance perception. As noted earlier, Gibson et al. (1955) found that perception of the extent of the tunnel itself was affected by density, namely, the denser the tunnel the longer it appeared. The variability of those judgments also increased with density. But when objects were embedded within the tunnel, its surface density influenced neither the perceived distance of those objects nor the reliability of those reports. However, the sparse and dense conditions used here were four times denser than those used in Gibson et al. It is possible that the accuracy or reliability of distance perception might show an abrupt change as density systematically increases or decreases to extreme values, suggesting a nonlinearity in distance perception (cf. Kelso, 1995). Future research is necessary to assess this possibility.

Chapter 4: Ecological Perspective on the Effects of Vista Space

Experiment 3A

Sequential integration operates from the observation point to the target. Consequently, the SSIP hypothesis would predict that manipulation of surface layout posterior to the target should not matter to distance perception. For the ecological theory, however, tying perceived distance to invariant optical structure from the surface layout means that *global* surface structure is important to distance perception, even if that structure occurs beyond the range of SSIP's sequential integration. The findings that information about the scale of environmental space affects distance perception (e.g., Gajewski, Wallin, & Philbeck, 2014) may be consistent with this prediction. Thus, for the ecological theory, the global surface structure beyond the range of sequential integration from the observation point to the target, should affect distance perception. The prediction for the present experiment is that the manipulation of the surface layout posterior to the target will affect distance perception of target in the intermediate distance range (> 2 m), which needs sequential integration of depth cues from the SSIP's view.

Method

Participants. Twenty students (7 male and 13 female) at the University of Connecticut participated in partial fulfillment of a course requirement. Ages ranged from 18 to 27 years. Sixteen of them were right-eye dominant and four were left-eye dominant. The Institutional Review Board (IRB) of the university approved all experimental procedures. Oral informed consent was obtained from each participant at the start of the experiment.

Apparatus and materials. In Experiments 3A and 3B, the discontinuity occurred at .5L (2 m from the observation point) and .75L (3 m from the observation point), thereby creating three domains relative to the discontinuity points: near-space (0 – 2 m), middle-space (2 – 3 m),

and far-space (3 – 4 m). The physical density of concentric rings in the three domains could be separately manipulated between dense and sparse as defined in Experiment 2A. In Experiment 3A, each of the middle- and far-spaces was manipulated between dense and sparse, whereas the near-space was always sparse. In consequence, the discontinuity of the tunnel was manipulated in three ways: (1) zero-discontinuity condition: continuously sparse throughout the tunnel, (2) one-discontinuity condition: near-space sparse/middle- and far-spaces dense, and (3) two-discontinuity condition: near-space sparse/middle-space dense/far-space sparse (Figure 10a). The target, target locations, and distance-reporting instrument were the same as in Experiment 2.

< Figure 10a-b About Here >

Design and Procedure. Experiment 3A was a 3 Discontinuity (zero discontinuity: sparse/sparse/sparse vs. one discontinuity: sparse/dense/dense vs. two discontinuity: sparse/dense/sparse) \times 3 Target location (.375L, .625L and .875L, with each target located in the middle of each spatial domain) within-subject design with 4 repetitions of each combination (Note that the one-discontinuity condition is the same as the discontinuous condition in Experiment 2B). The total 36 trials were divided into 12 blocks (3 discontinuity \times 4 repetitions), each of which had 3 trials for the 3 target locations: Each block had a single discontinuity condition (i.e., zero-, one- or two-discontinuity) with each of the three target locations. The order was completely randomized between and within blocks across participants. The magnitude production task was the same as in Experiment 2.

Specific Predictions. The main prediction from the ecological theory is that perceived distance for the .625L target should differ in accuracy between the one- and two-discontinuity conditions due to the different posterior structure in far-space. For the .875L target, however, the prediction from the ecological theory is rather exploratory. Perceived distance may differ in

accuracy among all discontinuity conditions due to the different surface layouts, but the direction of the difference is not certain. For the .875L target, in contrast, SSIP would predict that perceived distance should be the shortest for the two-discontinuity condition, longer for the one-discontinuity condition, and the longest for the zero-discontinuity condition, according to where the discontinuity restarts sequential integration.

Results

Means of D' with standard deviations are shown in Table 6. A 3 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on D' confirmed that D' increased with D , $F(2, 38) = 1328.09$, $p < .001$, $\eta_p^2 = .986$. With regard to the discontinuity manipulation, D' was significantly different among the discontinuity conditions, $F(2, 38) = 11.55$, $p < .001$, $\eta_p^2 = .378$; Means were 218.20 ($SE = 5.84$) for the zero-discontinuity condition, 213.93 ($SE = 4.75$) for the one-discontinuity condition, and 219.13 ($SE = 4.75$) for the two-discontinuity condition. The Discontinuity \times Location interaction was also significant, $F(4, 76) = 3.26$, $p = .016$, $\eta_p^2 = .147$. Planned ANOVA tests for discontinuity with Bonferroni correction revealed that (1) D' did not significantly differ for the discontinuity manipulation at .375L, $F(2, 38) = 3.38$, $p = .134$, $\eta_p^2 = .151$, (2) D' did significantly differ for the discontinuity manipulation at .625L, $F(2, 38) = 11.11$, $p < .001$, $\eta_p^2 = .369$, and (3) D' did not significantly differ for the discontinuity manipulation at .875L, $F(2, 38) = 2.81$, $p = .218$, $\eta_p^2 = .129$. For (2), planned pairwise comparisons for discontinuity with Bonferroni correction were further conducted revealing that, at .625L, D' was significantly smaller for the one-discontinuity condition ($M = 208.61$, $SE = 7.37$) than for the two-discontinuity condition ($M = 218.21$, $SE = 7.56$), $t(19) = 4.34$, $p = .001$, and also than for the zero-discontinuity condition ($M = 215.28$, $SE = 7.05$), $t(19) = 3.17$, $p = .015$, but the latter two did not differ from each other, $t(19) = 1.51$, $p = .440$. For (3), planned pairwise

comparisons further showed that, at .875L, D' of the one-discontinuity condition ($M = 316.40$, $SE = 7.12$) was significantly smaller than D' of the zero-discontinuity condition ($M = 319.59$, $SE = 7.22$), $t(19) = 2.88$, $p = .029$, but not significantly different from D' of the two-discontinuity condition ($M = 319.76$, $SE = 7.74$), $t(19) = 1.78$, $p = .275$.

< Table 6 About Here >

Figure 11a presents the results of MRS_{error} . A 3 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on MRS_{error} showed that MRS_{error} was significantly different among the target locations, $F(2, 38) = 11.65$, $p < .001$, $\eta_p^2 = .380$. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that MRS_{error} at .875L ($M = 11.26$, $SE = 1.79$) was significantly smaller than MRS_{error} at .625L ($M = 15.21$, $SE = 2.70$), $t(19) = 3.17$, $p = .015$, and also than MRS_{error} at .375L ($M = 18.39$, $SE = 2.86$), $t(19) = 4.06$, $p = .002$. With respect to the discontinuity manipulation, MRS_{error} was significantly different among the discontinuity conditions, $F(2, 38) = 7.22$, $p = .002$, $\eta_p^2 = .275$; Means were 14.36 ($SE = 2.26$) for the zero-discontinuity condition, 16.10 ($SE = 2.46$) for the one-discontinuity condition, and 14.40 ($SE = 2.36$) for the two-discontinuity condition. The Discontinuity \times Location interaction was only marginally significant, $F(4, 76) = 2.38$, $p = .059$, $\eta_p^2 = .111$. Planned ANOVA tests for discontinuity with Bonferroni correction revealed that (1) MRS_{error} did not significantly differ for the discontinuity manipulation at .375L, $F(2, 38) = 3.78$, $p = .095$, $\eta_p^2 = .166$, nor at .875L, $F(2, 38) = .62$, $p = 1.00$, $\eta_p^2 = .032$, but (2) MRS_{error} did significantly differ for the discontinuity manipulation at .625L, $F(2, 38) = 7.24$, $p = .006$, $\eta_p^2 = .276$. For (2), planned pairwise comparisons for discontinuity with Bonferroni correction were further conducted revealing that, at .625L, MRS_{error} was significantly larger for the one-discontinuity condition ($M = 17.00$, $SE = 2.84$) than for the two-discontinuity condition ($M = 14.14$, $SE = 2.72$), $t(19) = 3.19$, $p = .014$, and

also than for the zero-discontinuity condition ($M = 14.50$, $SE = 2.66$), $t(19) = 3.01$, $p = .021$, but the latter two did not differ from each other, $t(19) = .51$, $p = 1.00$.

< Figure 11a-b About Here >

Figure 11b demonstrates the results of *AD*. A 3 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on *AD* showed that *AD* did not differ for the discontinuity manipulation, $F(2, 38) = .17$, $p = .849$, $\eta_p^2 = .009$; Means were 4.07 ($SE = .56$) for the zero-discontinuity condition, 4.08 ($SE = .53$) for the one-discontinuity condition, and 4.22 ($SE = .62$) for the two-discontinuity condition. Also, the Discontinuity \times Location interaction was not significant, $F(4, 76) = .21$, $p = .935$, $\eta_p^2 = .011$. *AD*, however, was significantly different among the target locations, $F(2, 38) = 5.74$, $p = .007$, $\eta_p^2 = .232$; Means were 4.85 ($SE = .73$) at .375L, 4.32 ($SE = .65$) at .625L, and 3.19 ($SE = .43$) at .875L. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that *AD* at .875L was significantly smaller than *AD* at .375L, $t(19) = 3.80$, $p = .004$, but not significantly different from *AD* at .625L, $t(19) = 2.00$, $p = .180$.

To examine differences between systematic error and random error, a 2 (Measure: *MRS_{error}*, *AD*) \times 3 (Discontinuity) ANOVA was conducted on the magnitude of error, averaged across the three target locations. *MRS_{error}* ($M = 14.95$, $SE = 2.34$) was significantly larger than *AD* ($M = 4.12$, $SE = .55$), $F(1, 19) = 31.13$, $p < .001$, $\eta_p^2 = .621$. The effect of discontinuity was significant, $F(2, 38) = 4.85$, $p = .013$, $\eta_p^2 = .203$. The Measure \times Density interaction was also significant, $F(2, 38) = 6.51$, $p = .004$, $\eta_p^2 = .255$. Planned pairwise comparisons for measure with Bonferroni correction further showed that *MRS_{error}* was significantly larger than *AD* in the zero-discontinuity condition, $t(19) = 5.72$, $p < .001$, in the one-discontinuity condition, $t(19) = 5.54$, $p < .001$, and in the two-discontinuity condition, $t(19) = 5.30$, $p < .001$.

Discussion

Experiment 3A aimed to investigate the effect of surface layout posterior to the target in the optical tunnel. For the .625L target, the ecological theory predicted a difference in D' between the one-discontinuity and two-discontinuity conditions, whereas the SSIP predicted no difference in D' . MRS_{error} was expected to show the same pattern of results as in D' .

The analysis of D' and MRS_{error} showed that D' at .625L was more underestimated (i.e., less accurate) on the one-discontinuity surface layout compared to (1) the zero-discontinuity layout, replicating Experiment 2B, and (2) the two-discontinuity layout, satisfying the prediction of the ecological theory. The manipulation of surface layout posterior to the target affected D' and its accuracy, suggesting that the global surface layout matters to distance perception in the intermediate distance range (> 2 m). This point is further supported by the additional result that D' at .625L was not different between the zero-discontinuity and two-discontinuity layouts: In spite of the discontinuity point at the half, D' did not decrease for the two-discontinuity condition presumably due to the posterior surface layout. The importance of the surface layout beyond the range of SSIP's integration refutes the SSIP by itself.

A previous study by Witt, Stefanucci, Riener, and Proffitt (2007) showed that perceived distance could be affected by the manipulations of the viewable range of space (both indoor and outdoor) beyond the target: When the endpoint of the surrounding space was closer to the target, perceived distance was larger. In their study, however, the different endpoints of the environment between the manipulations may have provided information about the scale of the environmental space, resulting in different perceived distance (e.g., Gajewski, Wallin, & Philbeck, 2014). In the present study, the endpoint of the surrounding space was held constant, and only the structural surface layout was manipulated. Further, the finding that D' at .875L did not differ between the

one-discontinuity and two-discontinuity conditions suggests that scaling of the optical tunnel's surrounding space was indifferent to the two surface layouts.

Additionally, for the .875L target, D' in the one-discontinuity layout was more underestimated than D' in the zero-discontinuity layout, as shown in Experiment 2B, but not different from D' on the two-discontinuity layout; D' was not different between the latter two. This observed order is not consistent with the order predicted by SSIP according to where the discontinuity restarts sequential integration. However, given the exploratory nature of the ecological theory's predictions (that D' might be different for different discontinuity conditions) and the potential anchoring effect for this target location, it would be premature to draw a firm conclusion at this point.

Further, the AD analyses showed that the discontinuity manipulation did not affect AD , favoring the ecological theory under the same logic in Experiments 2A and 2B. Additionally, the analyses with target location showed that MRS_{error} was smaller at .875L than at .375L and at .625L, and AD was smaller at .875L than at .375L, with the smallest mean MRS_{error} and AD at .875L, suggesting the possibility of anchoring effect as in Experiments 2A and 2B.

Lastly, the fact that systematic error (MRS_{error}) was larger than the random error (AD) in all tunnels (i.e., zero-, one-, and two-discontinuity) indicates that distance perception was influenced by the structural properties of the optical tunnel's surface layout, not simply D *per se*. A smooth integration process anchored in reliable depth cues (He et al., 2004; Wu et al., 2004) should have produced accurate distance perception at least for the continuous tunnel, but did not. In the ecological perspective, the observed systematic error in absolute distance perception, using D as an artificial criterion, would presumably be due to non-obvious optical variables generated by the optical tunnel's surface layout (Kim et al., 2016).

In summary, the accuracy of D' was affected by the manipulation of the surface layout posterior to the target. The global surface layout beyond the range of sequential integration from the observation point to the target, mattered to distance perception. In addition, the reliability of D' did not differ among the differently manipulated surface layouts, and the observed systematic error was not accountable by the SSIP. All these results support the concept of a specifying optical invariant for distance in the ecological theory rather than that of sequential integration in the SSIP.

Experiment 3B

The results of Experiment 3A favor the assumption of the ecological theory that the global surface layout affects distance perception. However, a limitation is that the number of discontinuities differed between the one-discontinuity and the two-discontinuity conditions. To confirm that the results of Experiment 3A were not due to the number of discontinuities, the same kind of experiment was repeated in Experiment 3B with only zero- and one-discontinuity conditions, the latter with the discontinuity at different locations. The prediction is the same as in Experiment 3A: The manipulation of surface layout posterior to the target will affect distance perception of a target in the intermediate distance range (> 2 m).

Method

Participants. Twenty students (5 male and 15 female) at the University of Connecticut participated in partial fulfillment of a course requirement. Ages ranged from 18 to 21 years. Fourteen of them were right-eye dominant and six were left-eye dominant. The Institutional Review Board (IRB) of the university approved all experimental procedures. Oral informed consent was obtained from each participant at the start of the experiment.

Apparatus and materials. As noted in Experiment 3A, the discontinuity occurred at .5L and .75L, distinguishing near-space (0 – 2 m), middle-space (2 – 3 m), and far-space (3 – 4 m) of the tunnel. In Experiment 3B, the three discontinuity conditions were (1) zero-discontinuity: continuously sparse throughout the tunnel, (2) one-discontinuity-at-.5L: near-space sparse/middle- and far-spaces dense, and (3) one-discontinuity-at-.75L: near- and middle- spaces sparse/far-space dense (Figure 10b). The target, target locations, and the distance-reporting instrument were the same as in previous experiments.

Design and Apparatus. Experiment 3B was a 3 Discontinuity (zero, one discontinuity at .5L, and one discontinuity at .75L) \times 3 Target location (.375L, .625L and .875L) within-subject design with 4 repetitions of each combination. The same magnitude production procedure and the same randomization method as in Experiment 3A were used.

Specific Predictions. The main prediction from the ecological theory is that for the .625L target, perceived distance should differ in accuracy between the zero-discontinuity condition and the one-discontinuity at .75L condition due to the different posterior structure in the far-space. (Note that the focal comparisons are different from those in Experiment 3A.) For the .875L target, the prediction from the ecological theory is again exploratory; perceived distance may differ in accuracy among all the three discontinuity conditions due to the different surface layouts, but the direction of the difference is not certain. As in Experiment 3A, predictions for SSIP would reflect where the discontinuity restarts sequential integration. For the .875L target, perceived distance should be the shortest for the one-discontinuity at .75L, longer for the one-discontinuity at .5L, and longest for the zero-discontinuity condition.

Results

Means of D' with standard deviations are shown in Table 7. A 3 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on D' confirmed that D' increased with D , $F(2, 38) = 3391.37$, $p < .001$, $\eta_p^2 = .994$. With regard to the discontinuity manipulation, D' was significantly different among the discontinuity conditions, $F(2, 38) = 11.07$, $p < .001$, $\eta_p^2 = .368$; Means were 220.70 ($SE = 4.05$) for the zero-discontinuity condition, 216.74 ($SE = 4.06$) for the one-discontinuity-at-.5L condition, and 216.86 ($SE = 4.05$) for the one-discontinuity-at-.75L condition. The Discontinuity \times Location interaction was also significant, $F(4, 76) = 3.86$, $p = .007$, $\eta_p^2 = .169$. Planned ANOVA tests for discontinuity with Bonferroni correction revealed that (1) D' did not significantly differ for the discontinuity manipulation at .375L, $F(1.59, 30.14) = 1.07$, $p = .354$, $\eta_p^2 = .053$, (2) D' did significantly differ for the discontinuity manipulation at .625L, $F(2, 38) = 10.37$, $p < .001$, $\eta_p^2 = .353$, and (3) D' also significantly differed for the discontinuity manipulation at .875L, $F(2, 38) = 7.22$, $p = .002$, $\eta_p^2 = .275$. For (2), planned pairwise comparisons for discontinuity with Bonferroni correction were further conducted revealing that, at .625L, D' of the one-discontinuity-at-.75L condition ($M = 208.93$, $SE = 4.88$) was significantly smaller than D' of the zero-discontinuity condition ($M = 215.35$, $SE = 4.96$), $t(19) = 4.37$, $p = .001$, but not was not significantly different from D' of the one-discontinuity-at-.5L condition ($M = 211.73$, $SE = 4.91$), $t(19) = 2.12$, $p = .142$, and the latter two only marginally differed from each other, $t(19) = 2.50$, $p = .065$. For (3), planned pairwise comparisons further showed that, at .875L, D' of the one-discontinuity-at-.5L condition ($M = 321.60$, $SE = 4.38$) was significantly smaller than D' of the zero-discontinuity condition ($M = 328.31$, $SE = 4.39$), $t(19) = 3.71$, $p = .004$, but not significantly different from D' of the one-discontinuity-at-.75L condition ($M = 324.63$, $SE = 4.42$), $t(19) = 1.87$, $p = .229$, and the latter two did not differ from each other, $t(19) = 1.97$, $p = .192$.

< Table 6 About Here >

Figure 12a illustrates the results of MRS_{error} . A 3 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on MRS_{error} showed that MRS_{error} significantly decreased with D , $F(1.23, 23.38) = 31.11, p < .001, \eta_p^2 = .621$. Post-hoc pairwise comparisons for target location with Bonferroni correction revealed that MRS_{error} at .875L ($M = 8.64, SE = 1.16$) was significantly smaller than MRS_{error} at .625L ($M = 15.33, SE = 1.90$), $t(19) = 5.85, p < .001$, and also than MRS_{error} at .375L ($M = 19.00, SE = 2.48$), $t(19) = 5.79, p < .001$, and further, MRS_{error} at .625L was significantly smaller than MRS_{error} at .375L, $t(19) = 4.07, p = .002$. With regard to the discontinuity manipulation, MRS_{error} was significantly different among the discontinuity conditions, $F(1.59, 30.28) = 7.61, p = .004, \eta_p^2 = .286$; Means were 13.37 ($SE = 1.79$) for the zero-discontinuity condition, 14.75 ($SE = 1.79$) for the one-discontinuity-at-.5L condition, and 14.84 ($SE = 1.76$) for the one-discontinuity-at-.75L condition. The Discontinuity \times Location interaction was not significant, $F(4, 76) = 1.87, p = .125, \eta_p^2 = .090$. Planned ANOVA tests for discontinuity with Bonferroni correction revealed that (1) MRS_{error} did not significantly differ for the discontinuity manipulation at .375L, $F(1.59, 30.14) = 1.07, p = .343, \eta_p^2 = .053$, (2) MRS_{error} did significantly differ for the discontinuity manipulation at .625L, $F(2, 38) = 9.68, p < .001, \eta_p^2 = .337$, and (3) MRS_{error} also significantly differed for the discontinuity manipulation at .875L, $F(2, 38) = 6.92, p = .003, \eta_p^2 = .267$. For (2), planned pairwise comparisons for discontinuity with Bonferroni correction were further conducted revealing that, at .625L, MRS_{error} of the zero-discontinuity condition ($M = 14.08, SE = 1.91$) is significantly smaller than MRS_{error} of the one-discontinuity-at-.75L condition ($M = 16.53, SE = 1.92$), $t(19) = 4.09, p = .002$, but only marginally smaller than MRS_{error} of the one-discontinuity-at-.5L condition ($M = 15.38, SE = 1.95$), $t(19) = 2.37, p = .086$, but the latter two did not differ from each other, $t(19) = 2.21, p$

= .119. For (3), planned pairwise comparisons further revealed that, at .875L, MRS_{error} of the zero-discontinuity condition ($M = 7.71$, $SE = 1.18$) was significantly smaller than MRS_{error} of the one-discontinuity-at-.5L condition ($M = 9.49$, $SE = 1.21$), $t(19) = 3.45$, $p = .008$, but not significantly different from MRS_{error} of the one-discontinuity-at-.75L condition ($M = 8.71$, $SE = 1.19$), $t(19) = 2.04$, $p = .165$, and the latter two did not differ from each other, $t(19) = 1.82$, $p = .254$.

< Figure 12a-b About Here >

Figure 12b presents the results of AD . A 3 (Discontinuity) \times 3 (Target location) repeated measures ANOVA on AD showed that AD did not differ for the discontinuity manipulation, $F(2, 38) = .01$, $p = .992$, $\eta_p^2 = .000$; Means were 3.61 ($SE = .38$) for the zero-discontinuity condition, 3.64 ($SE = .40$) for the one-discontinuity-at-.5L condition, and 3.65 ($SE = .28$) for the one-discontinuity-at-.75L condition. The Discontinuity \times Location interaction was not significant either, $F(4, 76) = 1.35$, $p = .259$, $\eta_p^2 = .066$. AD , however, was significantly different among the target locations, $F(1.45, 27.54) = 6.88$, $p = .007$, $\eta_p^2 = .266$; Means were 3.70 ($SE = .28$) at .375L, 4.43 ($SE = .56$) at .625L, and 2.75 ($SE = .29$) at .875L. Post-hoc pairwise comparisons for target location with Bonferroni correction further showed that AD at .875L was significantly smaller than AD at .625L, $t(19) = 3.30$, $p = .011$, and also than AD at .375L, $t(19) = 3.61$, $p = .006$, but the latter two did not significantly differ from each other, $t(19) = 1.36$, $p = .569$.

To examine differences between systematic error and random error, a 2 (Measure: MRS_{error} , AD) \times 3 (Discontinuity) ANOVA was conducted on the magnitude of error, averaged across the three target locations. MRS_{error} ($M = 14.32$, $SE = 1.76$) was significantly larger than AD ($M = 3.63$, $SE = .30$), $F(1, 19) = 46.21$, $p < .001$, $\eta_p^2 = .709$. The effect of discontinuity was significant, $F(2, 38) = 4.41$, $p = .019$, $\eta_p^2 = .188$. The Measure \times Density interaction was also

significant, $F(2, 38) = 5.14, p = .011, \eta_p^2 = .213$. Planned pairwise comparisons for measure with Bonferroni correction further showed that MRS_{error} was significantly larger than AD in the zero-discontinuity condition, $t(19) = 6.12, p < .001$, in the one-discontinuity-at-.5L condition, $t(19) = 7.27, p < .001$, and in the one-discontinuity-at-.75L condition, $t(19) = 6.71, p < .001$.

Discussion

Experiment 3B aimed to confirm the effect of surface layout posterior to the target with only zero- and one-discontinuity tunnel layouts. For the .625L target, the ecological theory predicted a difference in D' between the zero-discontinuity and one-discontinuity-at-.75L conditions, whereas the SSIP predicted no difference between the two. MRS_{error} was expected to show the same pattern as D' .

The analysis of D' and MRS_{error} showed that D' at .625L was more underestimated on the one-discontinuity-at-.75L surface layout than on the zero-discontinuity layout, satisfying the prediction of the ecological theory. Moreover, D' at .625L was not different between the one-discontinuity-at-.5L and one-discontinuity-at-.75L layouts: Despite the continuous surface layout up to the target in the one-discontinuity-at-.75L condition, D' did not increase, presumably due to the change in the posterior surface structure. In brief, the surface layout beyond the range of integration matters to distance perception. On the other hand, there was only a marginal difference in D' between the one-discontinuity-at-.5L and zero-discontinuity tunnel layouts, which may qualify the discontinuity effect found in Experiments 2B and 3A. Although these post-hoc analyses were conducted under the conservative Bonferroni corrections, the robustness of the discontinuity effect would need further tests.

For the .875L target, the results of D' and MRS_{error} showed the same pattern as in Experiment 3A. D' on the one-discontinuity-at-.5L layout was more underestimated than D' on

the zero-discontinuity layout, but not different from D' on the one-discontinuity-at-.75L layout; D' did not differ between the latter two. The order predicted by SSIP, according to where the discontinuity restarts integration, is hard-pressed to explain this finding. However, due to the reasons mentioned in Experiment 3A, it would be difficult to draw a solid conclusion at the moment.

In addition, the AD analyses showed that, as in Experiment 3A, the discontinuity manipulation did not affect AD . The analyses with target location showed that MRS_{error} decreased with D , and AD was smaller at .875L than at .375L and at .625L, again implying the possibility of anchoring effect.

As in Experiment 3A, the systematic error (MRS_{error}) was larger than the random error (AD) in all the discontinuity tunnels, indicating that the structural properties of the optical tunnel's surface layout influenced distance perception beyond D *per se*. As explained above, the observed systematic error, especially for the zero-discontinuity tunnel, is not readily accountable by the SSIP's smooth integration process anchored in reliable depth cues. Instead, it is consistent with the effect of non-obvious optical variables generated by the optical tunnel's surface layout.

In summary, the manipulation of the surface structure posterior to the target affected D' , indicating the importance of the global surface layout in distance perception. Further, the reliability of D' did not differ, and the SSIP could not account for the observed systematic error in distance perception. In brief, Experiment 3B confirmed the findings of Experiment 3A, suggesting that those findings were not due to the number of discontinuities but due to the different optical invariants specifying distance, generated by the different global surface layouts.

Chapter 5: General Discussion

Objects in the environment are nested or embedded within larger-scale environmental entities. This embedding has been absent from experimental investigations of the perception of surface layout. In particular, researchers have typically not employed manipulations of an embedding environment with corresponding consequences for optical structure. The optical tunnel provides a means of controlling the embedding surface layout and the corresponding optical structure, whether characterized as the nesting and distribution of optical solid angles in the optic array (in an ecologically motivated approach) or visual angles in the proximal stimulus (in a computationally motivated approach).

The present dissertation aimed to find evidence of optical structure specific to distance perception in the optical tunnel. In order to delimit the exploratory nature of manipulations of the embedding structure, the reported experiments were constrained by predictions of two influential computational theories—the ground dominance effect hypothesis and the sequential surface integration process (SSIP) hypothesis. Expectations from an alternative framework provided by the ecological approach were also considered.

In Experiments 1A and 1B, the ground dominance hypothesis was evaluated in the optical tunnel setting which allows structural layout over the ground and ceiling surfaces to be equated. Experiment 1A showed no ground surface advantage in distance perception when the whole tunnel layout was visible. However, Experiment 1B revealed that when half of the tunnel was occluded, D' of the ceiling-mounted targets was larger and more accurate than D' of the ground-mounted targets. This result is clearly inconsistent with the ground dominance theory. The ecological approach, however, would encourage considering that the two optical structures are, in fact, different with respect to what amounts to a horizon. For example, the different

horizon relationships may specify different affordances (e.g., reach-ability) between the two targets. As an illustration, it was speculated that perceived distance is standing proxy for reach-ability. If so, the location of targets resting on the ground or hanging from the ceiling matters (e.g., Carello et al., 1989) due to the demands of postural adjustments, reaching against gravity, and so on. The optical structure *above* the horizon (from the ceiling) may provide a relevant optical invariant that scales the layout to the observer (Sedgwick, 1980, 1983). This conjecture needs further research with respect to both manipulating the horizon-ratio relationship and the explicit evaluation of the affordance rather than the behaviorally neutral property of distance.

Experiments 2A and 2B examined the texture discontinuity effect on distance perception. Both experiments showed that the reliability of distance perception did not differ whether the tunnel surface layout was continuous or discontinuous. The SSIP hypothesis, in asserting that a smooth sequential integration process is disrupted at a discontinuity boundary, is hard pressed to explain this result. Instead, this reliability pattern concurs well with the ecological theory that the visual system detects an optical invariant from the given surface layout regardless of whether it is continuous or discontinuous. Further, comparable findings for the shift from sparse to dense and dense to sparse confirmed that distance perception is not procedurally different in the two settings.

In Experiment 2C, the effect of texture density was investigated. The result also showed that the reliability of distance perception did not differ whether the tunnel surface layout was dense or sparse. This finding is contrary to the SSIP's prediction that a sequential integration process should be more efficient for more closely adjoined local surface patches, but consonant with the ecological theory that detection of an optical invariant is procedurally indifferent to whether the surface layout is dense or sparse.

In Experiments 3A and 3B, the ecological theory and the SSIP hypothesis were compared for the effect of vista space—the space beyond the fixated target (Witt et al., 2007). Both experiments showed that the accuracy of distance perception was affected by the manipulation of the vista space—the surface layout posterior to the target, beyond the range of sequential integration to the target. The global surface layout mattered to distance perception. These findings accord with the ecological theory’s concept of distance-specifying optical invariant generated by the global surface layout.

In summary, all three Experiments pose problems for the two leading computational theories that had adopted the ground theory. The evidence seems to favor the ecological theory of distance perception based on the optical tunnel’s structured surface layout. One common finding across all the experiments was that the reliability of distance perception did not differ whether the manipulation was of target position, texture discontinuity, or global surface layout. This finding dovetails with the ecological theory that visual perception detects an optical invariant from the given surface layout, rather than integrates cues sequentially or in any other complicated ways.

Another common finding was that the systematic error was larger than the random error, that is, $MRS_{error} > AD$. Such a difference is typically interpreted as an indication that the metric criterion—in the present case, absolute distance—is not the complete constraint on perception (Carello et al., 2006). These systematic differences indicate that the structural properties of the given surface layout influenced distance perception. The results of the present studies, however, suggest that this influence would not be due to a ground dominance effect nor a sequential surface integration process. We have argued that the influence is due to non-obvious optical variables generated by the given surface layout (Kim et al., 2016). Whereas distance as such

would be an obvious variable, ecological psychologists have long argued that information about a property is not the property itself (Fultot, Nie, & Carello, 2016; Gibson, 1966; Turvey & Shaw, 1995). Information about distance is not distance itself. In the ecological perspective, an optical invariant is globally defined. It may include both obvious (e.g., distance) and non-obvious optical variables (e.g., the continuity, density, and regularity of the surface gradient; deformations of those over time). “[T]his invariant property may be specific to a single collective parameter of relevant environmental properties, which is invariant over the time-varying optical dynamics of visual perception” (Kim et al., p. 10). The assumption of the ecological theory that the different optical invariants are tied to different perceived distances (or, more likely, different affordances) is consistent with the finding that significant differences in accuracy of distance perception were found in all three Experiments.

Although the main focus of Experiments 2 and 3 was on the targets in the intermediate distance range (far-space in Experiments 2A, 2B, and 2C, and middle- and far-spaces in Experiments 3A and 3B), the results for the near-space target (at .375L) also support the ecological theory. One more common finding across all the experiments was that neither accuracy nor reliability of distance perception was better for the closest target (at .375L) than the others, which is contrary to the assumption of the computational theories that the visual system represents the near ground surface accurately with reliable near depth cues (He et al., 2004; Loomis, et al., 1996; Wu et al., 2004). As noted, the potential anchoring effect for the farthest target (at .875L) due to the adjacent endpoints of the tunnel and the reporting device might explain the better accuracy and reliability for that target. However, the findings that (1) the accuracy of .375L target did not differ from or was less than that of .625L target and (2) the

reliability of .375L target did not differ from that of .625L target could be explained by the ecological theory's notion of detecting an optical invariant.

One final interesting finding was that the accuracy of perceived distance did not differ for the closest target (at .375L) whether there is a discontinuity or not in both Experiments 2 and 3. The manipulations of the posterior layout did not affect distance perception for the target in the near-space. Future study is necessary to examine whether an optical invariant specifying distance is different between near-space and far-space with regard to non-obvious optical variables from the posterior surface layout. This may be where the affordance reconceptualization comes to forefront as distinctions in the manner of reaching (e.g., with one arm, bending at the hip, taking a step, etc.) become important (Carello et al., 1989).

In conclusion, the present dissertation provides evidence that optical structure specific to distance is available in the optical tunnel. It provides the foundation for future studies that can evaluate the role of the horizon, changes in texture gradient, distinct distant-related affordances and, in particular, differences between near-space and far-space, and so on, to provide a deeper understanding of invariant optical structure. The present study also revealed that the too-long neglected optical tunnel could provide a fruitful method to investigate such issues. Ultimately, manipulation of the optical tunnel will allow exploration of what might constitute the relevant collective parameter (i.e., higher-order optical variable) that specifies an environmental property such as distance. Uncovering a systematic influence of the gradient of the structured surface layout—its continuity, density, regularity, and any other properties anterior and posterior to the target—on various environmental properties would provide a novel contribution to our understanding of perception of the visual world.

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Figure Captions

Figure 1. An optical tunnel consists of a series of concentric apertures in alternately black and white surfaces hanging behind one another, perpendicular to the line of sight.

Figure 2. A chinrest supports the head so that the dominant eye is centered with respect to the viewing aperture. The report apparatus is a crank and pulley system that allows the observer to adjust the position of a vertical marker, a black hexagon at the height of the target, affixed to a metal rail extending 4.2 m from the right hand of the observer. A black occluding curtain was draped between the tunnel and the report apparatus.

Figure 3. In Experiment 1A, the target can be attached to (a) the ground or (b) the ceiling of the tunnel. In Experiment 1B, a barrier at the viewing aperture blocks (c) the ceiling structure for a target on the ground or (d) the ground structure for a target attached to the ceiling.

Figure 4. (a) MRS_{error} and (b) AD as a function of target location and position in Experiment 1A.

Figure 5. (a) MRS_{error} and (b) AD as a function of target location and position in Experiment 1B.

Figure 6. The tunnel discontinuity is manipulated (a) in Experiment 2A, between the continuous condition (near-space dense/far-space dense) and the discontinuous condition (near-space dense/far-space sparse), or (b) in Experiment 2B, between the continuous condition (near-space sparse/far-space sparse) and the discontinuous condition (near-space sparse/far-space dense). (c) The tunnel density is manipulated in Experiment 2C, between the dense condition (near- and far-spaces dense) and the sparse condition (near- and far-spaces sparse).

Figure 7. (a) MRS_{error} and (b) AD as a function of target location and tunnel discontinuity in Experiment 2A.

Figure 8. (a) MRS_{error} and (b) AD as a function of target location and tunnel discontinuity in Experiment 2B.

Figure 9. (a) MRS_{error} and (b) AD as a function of target location and tunnel density in Experiment 2C.

Figure 10. The tunnel discontinuity is manipulated (a) in Experiment 3A, among the zero-discontinuity condition (continuously sparse), the one-discontinuity condition (near-space sparse/middle- and far-spaces dense), and the two-discontinuity condition (near-space sparse/middle-space dense/far-space sparse), or (b) in Experiment 3B, among the zero-discontinuity condition (continuously sparse), the one-discontinuity-at-.5L condition (near-space sparse/middle- and far-spaces dense), and the one-discontinuity-at-.75L condition (near- and middle- spaces sparse/far-space dense).

Figure 11. (a) MRS_{error} and (b) AD as a function of target location and tunnel discontinuity in Experiment 3A.

Figure 12. (a) MRS_{error} and (b) AD as a function of target location and tunnel discontinuity in Experiment 3B.

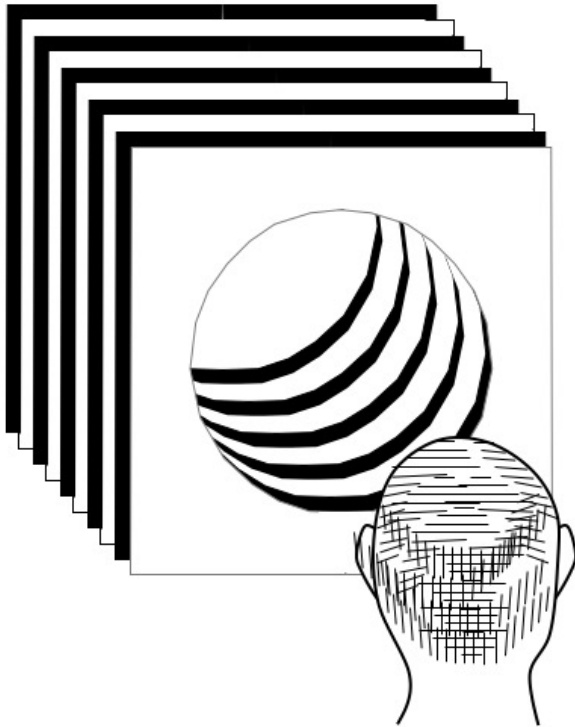


Figure 1

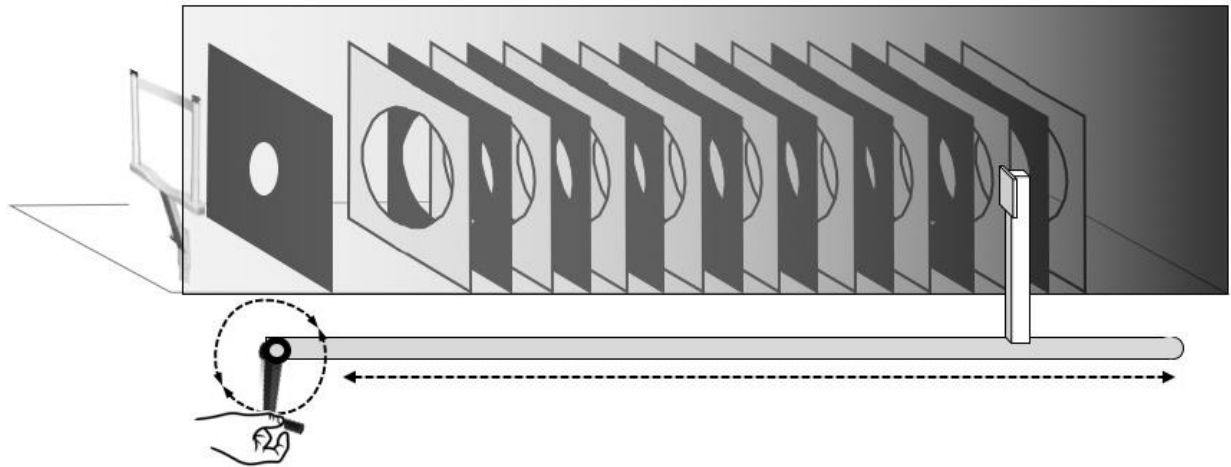


Figure 2

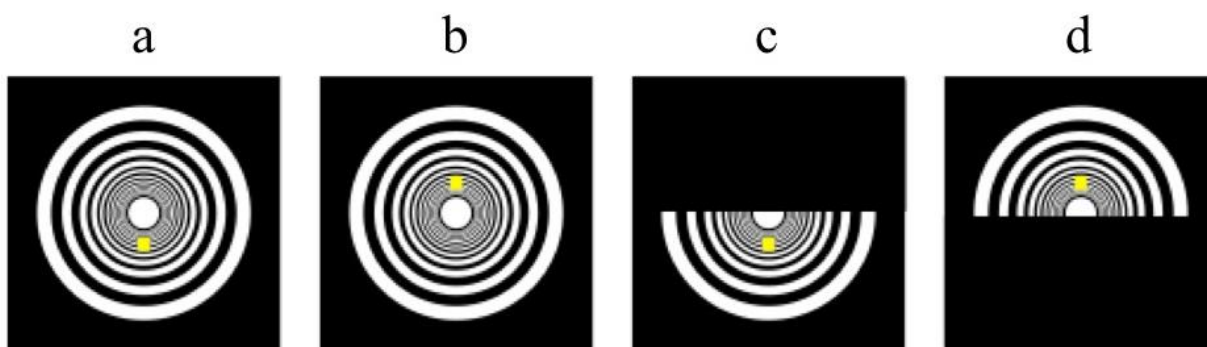


Figure 3

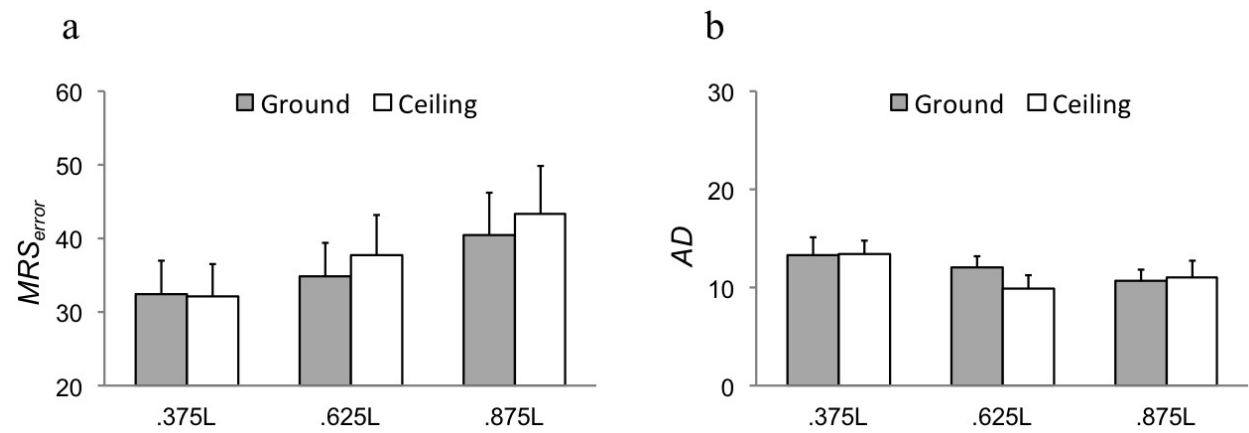


Figure 4

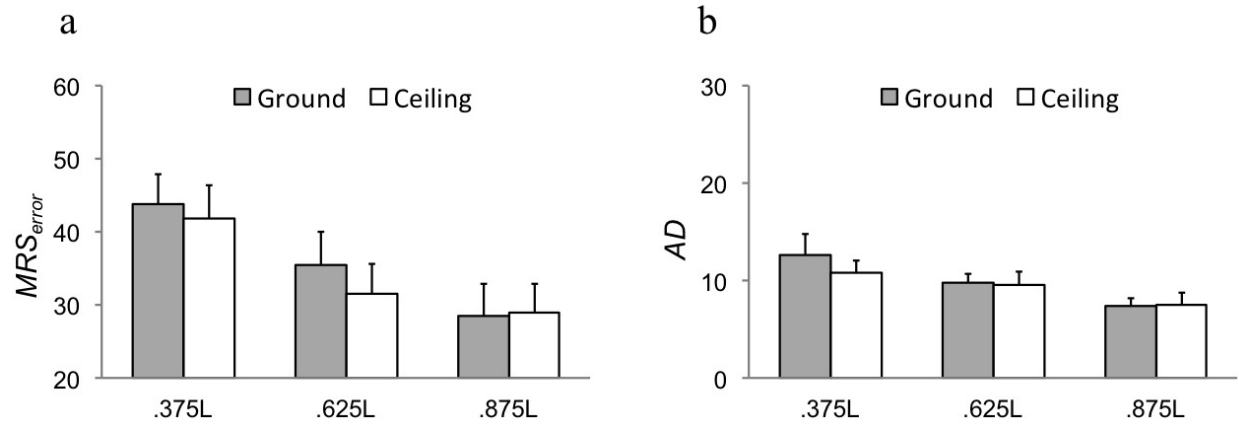


Figure 5

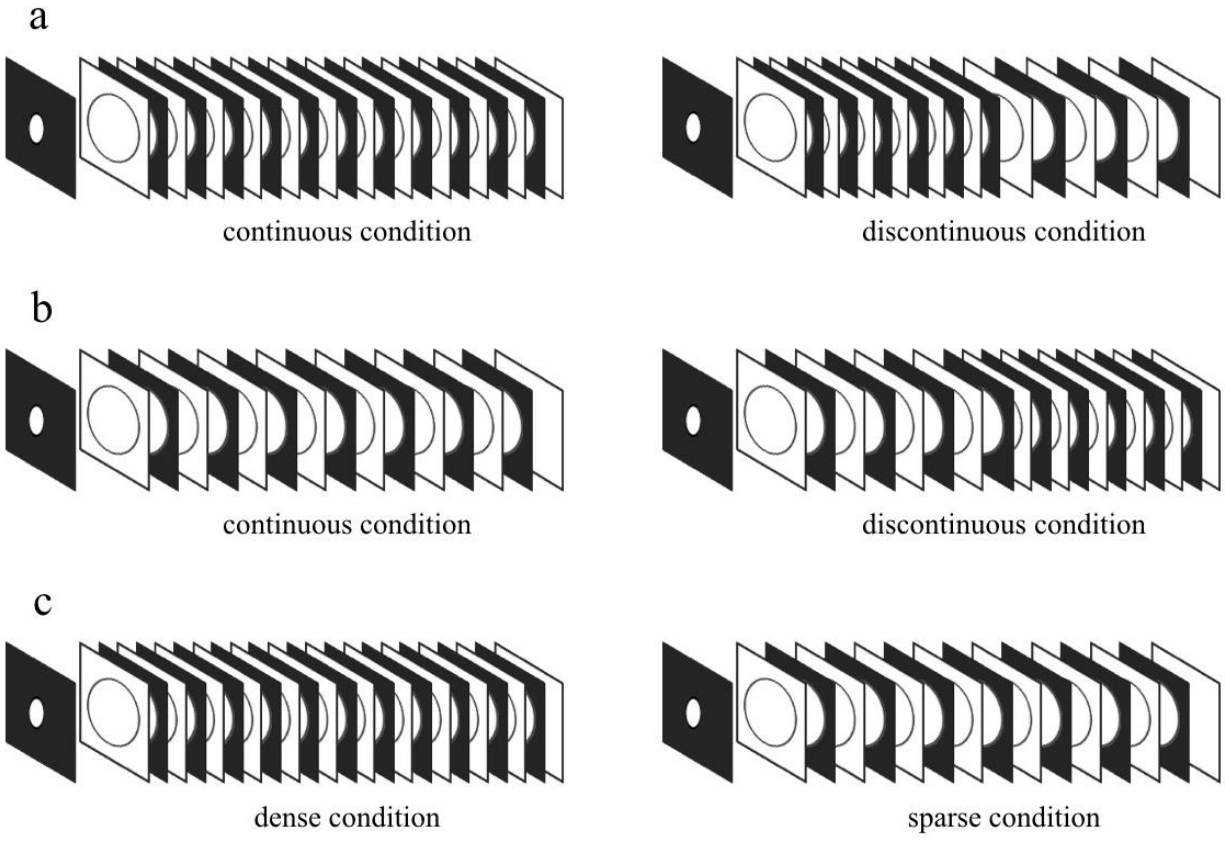


Figure 6

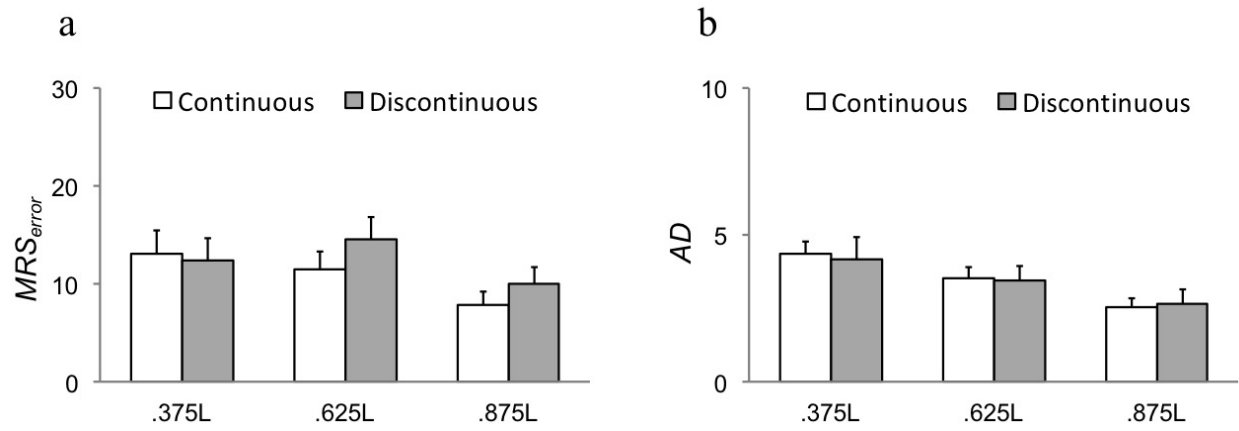


Figure 7

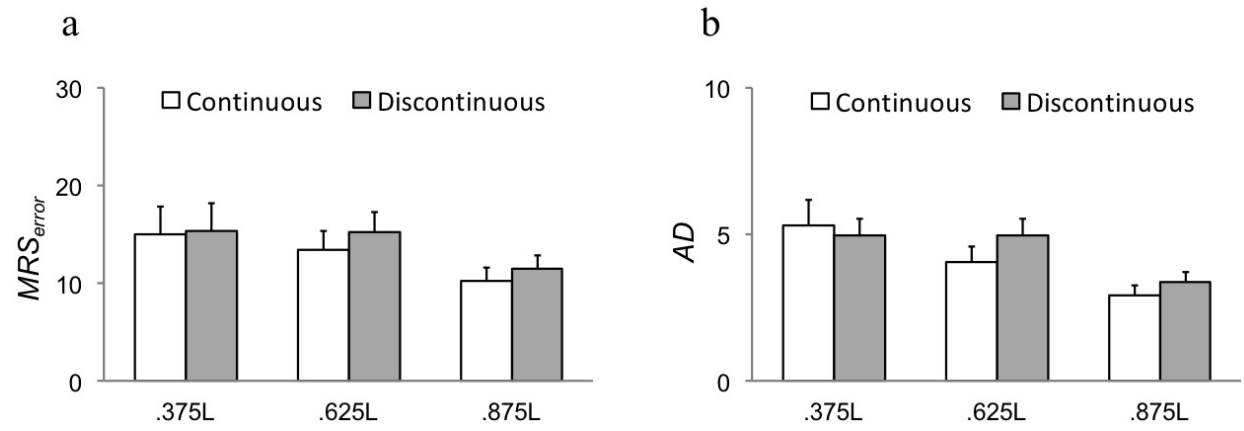


Figure 8

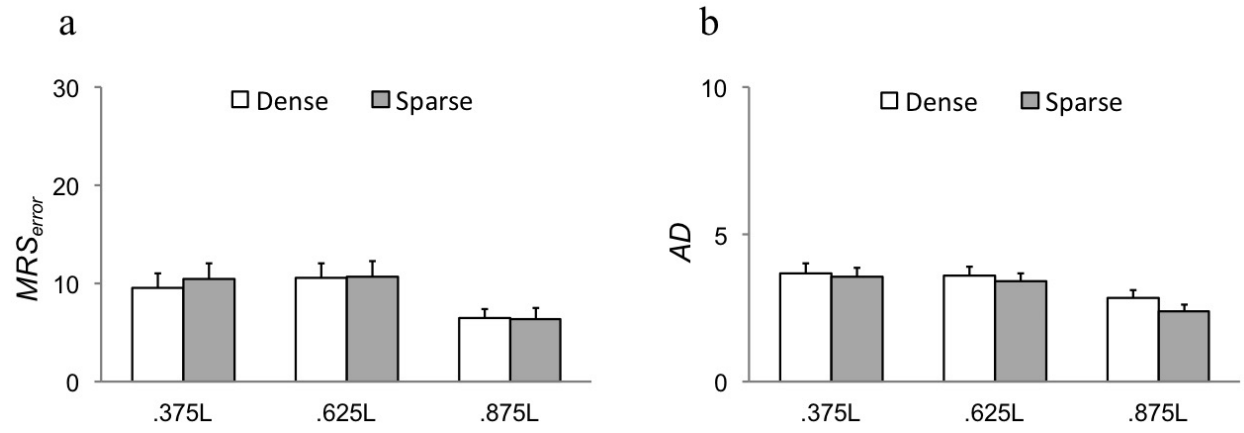


Figure 9

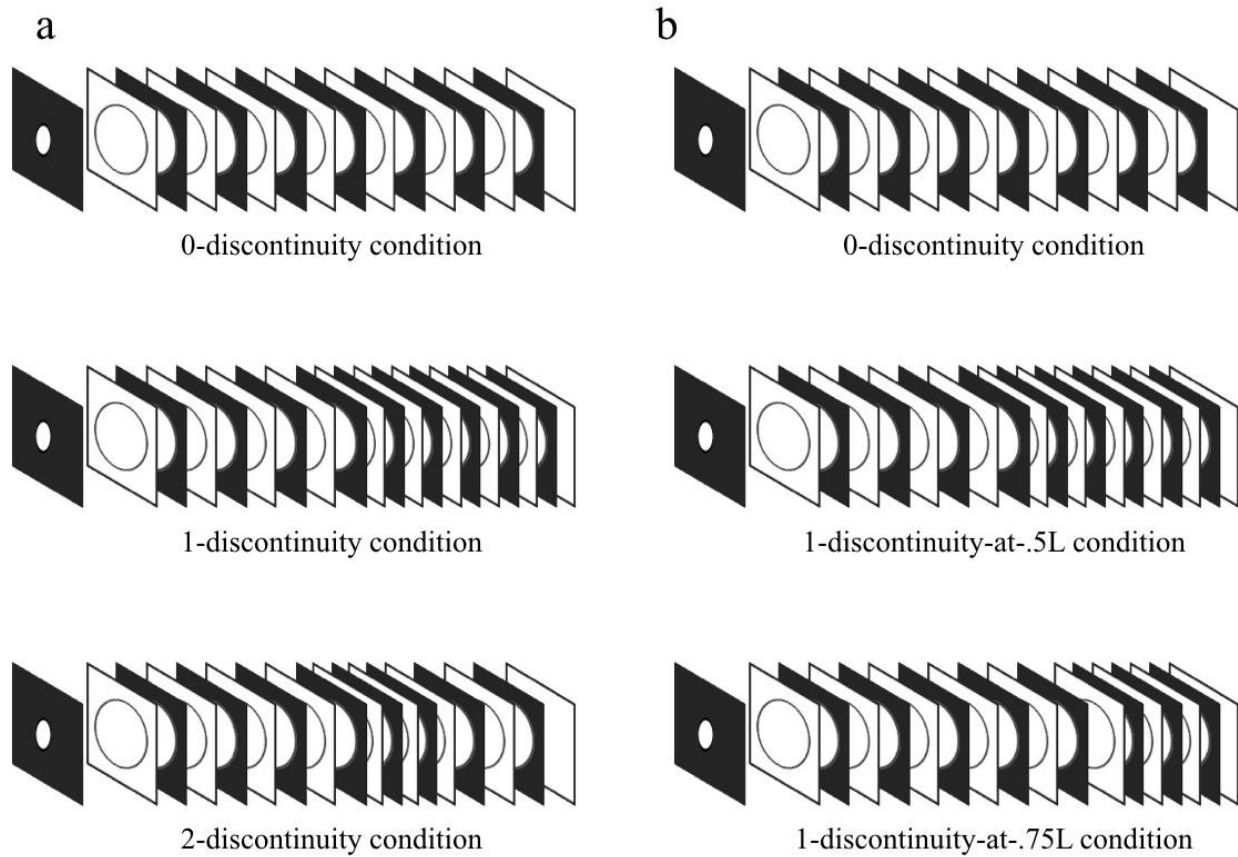


Figure 10

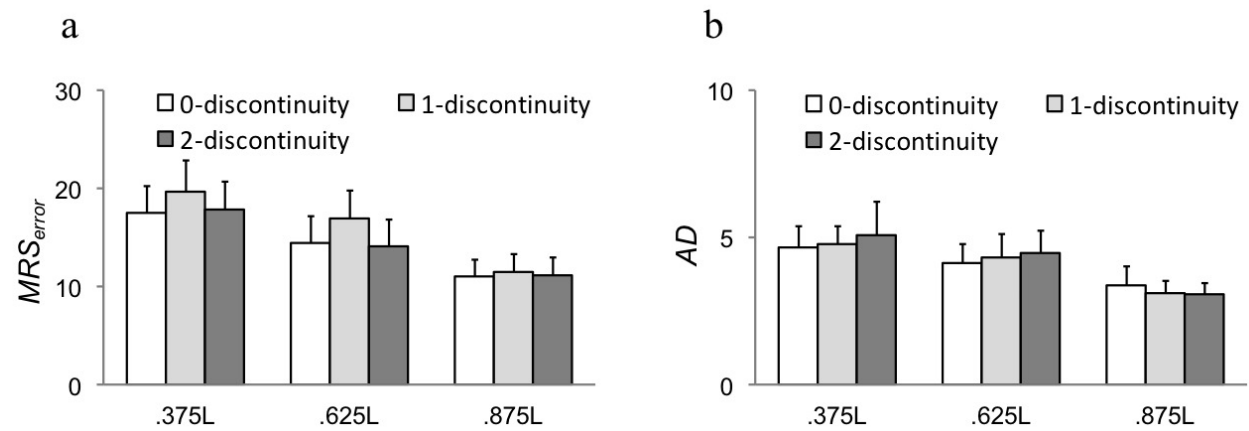


Figure 11

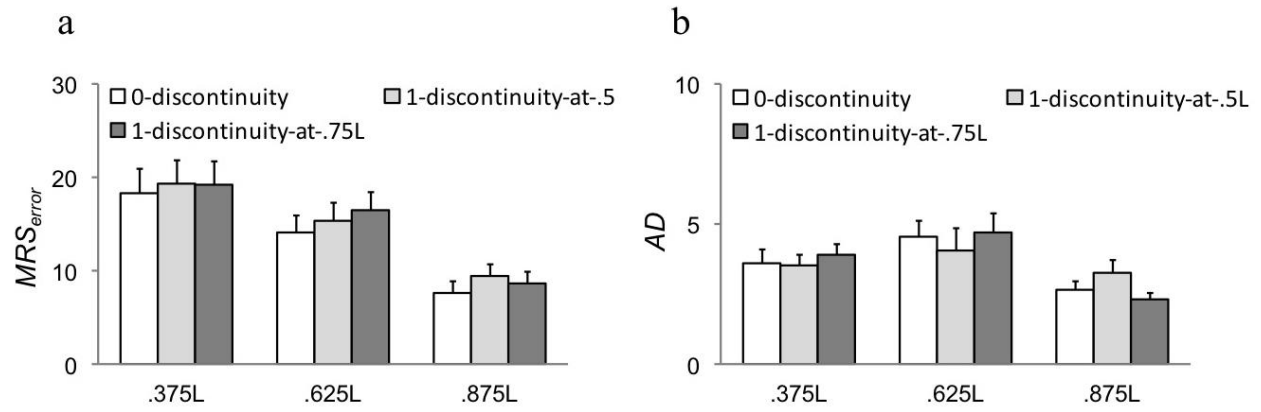


Figure 12

Table 1

Mean perceived distance (D' in cm) as a function of target location and position in Experiment 1A.

	Target Position			
	Ground		Ceiling	
Target Location	D'	(SE)	D'	(SE)
145 (.325L)	105.98	8.25	113.36	9.64
250 (.625L)	220.92	21.79	248.47	25.05
355 (.875L)	365.82	38.43	384.54	41.17

Table 2

Mean perceived distance (D' in cm) as a function of target location and position in Experiment 1B.

	Target Position			
	Ground		Ceiling	
Target Location	D'	(SE)	D'	(SE)
145 (.325L)	81.59	6.07	85.40	7.06
250 (.625L)	164.17	12.45	182.03	13.60
355 (.875L)	270.04	19.94	284.99	22.29

Table 3

Mean perceived distance (D' in cm) as a function of target location and tunnel discontinuity in Experiment 2A.

	Tunnel Discontinuity			
	Continuous		Discontinuous	
Target Location	D'	(SE)	D'	(SE)
145 (.325L)	131.26	4.47	131.78	4.25
250 (.625L)	224.88	5.61	214.89	6.20
355 (.875L)	329.25	5.30	321.25	6.69

Table 4

Mean perceived distance (D' in cm) as a function of target location and tunnel discontinuity in Experiment 2B.

	Tunnel Discontinuity			
	Continuous		Discontinuous	
Target Location	D'	(SE)	D'	(SE)
145 (.325L)	124.43	4.37	123.90	4.36
250 (.625L)	216.81	5.06	212.27	5.30
355 (.875L)	320.22	5.34	314.94	5.22

Table 5

Mean perceived distance (D' in cm) as a function of target location and tunnel density in Experiment 2C.

	Tunnel Density			
	Dense		Sparse	
Target Location	D'	(SE)	D'	(SE)
145 (.325L)	134.27	2.81	132.78	3.01
250 (.625L)	224.30	3.77	224.97	4.47
355 (.875L)	335.22	4.22	337.43	5.24

Table 6

Mean perceived distance (D' in cm) as a function of target location and tunnel discontinuity in Experiment 3A.

	Tunnel Discontinuity					
	0-discontinuity		1-discontinuity		2-discontinuity	
Target Location	D'	(SE)	D'	(SE)	D'	(SE)
145 (.325L)	119.75	4.07	116.76	4.56	119.43	4.21
250 (.625L)	215.28	7.04	208.61	7.37	218.21	7.56
355 (.875L)	319.59	7.22	316.40	7.12	319.76	7.74

Table 7

Mean perceived distance (D' in cm) as a function of target location and tunnel discontinuity in Experiment 3B.

	Tunnel Discontinuity					
	0-discontinuity		1-discontinuity-at-.5L		1-discontinuity-at-.75L	
Target Location	D'	(SE)	D'	(SE)	D'	(SE)
145 (.325L)	118.43	3.85	116.89	3.60	117.04	3.52
250 (.625L)	215.35	4.96	211.73	4.91	208.93	4.88
355 (.875L)	328.31	4.39	321.60	4.39	324.63	4.42