

Visual Sensitivity Can Scale with Illusory Size Changes

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Summary

Retinal image size is not the sole determinant of the apparent size of objects. Rather, viewing distance is taken into account when determining apparent size [1–3], so images of the same physical dimensions can appear to represent different-sized objects. Here, we take advantage of this to examine the relationship between visual sensitivity and the scaling processes involved in determining apparent size. We assess the impact of illusory size changes, induced by apparent viewing distance changes, on judgments concerning clearly visible stimuli and on the ability to detect low-contrast inputs. We find that sensitivity to slight orientation changes between successive and clearly visible stimuli can scale with illusory size changes. However, illusory size changes have no discernable impact on the ability to detect low-contrast inputs. When considered in conjunction with recent brain imaging studies [4–6], our data suggest that visual sensitivity is linked to the spread of activity across primary visual cortex, which for clearly visible stimuli is shaped by the scaling processes involved in the determination of apparent size.

Results and Discussion

It is well established that visual sensitivity can scale with the size of retinal images [7, 8]. However, it is as yet unclear whether visual sensitivity also scales with illusory size changes. This question can be asked because viewing distance is taken into account when determining apparent size [1–3], so images of the same physical dimensions can appear to represent different-sized objects. As a result, cars do not seem to shrink as they move away from us, or to grow as they move toward us, despite the fact that the retinal images of cars in these cases do shrink and expand.

To explore the links between apparent size and visual sensitivity, we induced illusory size changes by manipulating a viewing distance cue that was extrinsic to our visual stimuli. Specifically, we manipulated the vergence angle of the eyes, which is changed by fixating objects at different distances in depth from the observer (see Figures 1A and 1B and Experimental Procedures; see also Supplemental Experimental Procedures available online). This manipulation created an impression that stimuli were located at viewing distances of either 45 or 90 cm, directly in front of the observer. Importantly, these changes were illusory—the actual viewing distance was constant. We first quantified the magnitude of the size illusion induced by this manipulation, by contrasting sequential stimuli at the discrepant apparent viewing distances. On average,

stimuli seemingly located 90 cm from the observer (far) appeared 25% ($\pm 3\%$) larger than physically matched stimuli apparently located 45 cm from the observer (near) (one-sample $t_5 = 8.07$, $p < 0.001$).

We then assessed sensitivity to orientation changes between clearly visible stimuli. Two successive stimuli were presented in each trial. The orientation of the first was vertical, and the orientation of the second was varied $\pm 1.25^\circ$ from vertical (see Figure 2A, Experimental Procedures, and Supplemental Experimental Procedures for further details). This allowed us to determine thresholds for discerning orientation changes for each of our participants. We did so for stimuli apparently located 45 cm from the observer (near), stimuli apparently located 90 cm from the observer (far), stimuli apparently located 45 cm from the observer scaled up in physical size to match the appearance of far stimuli (near upscaled), and stimuli apparently located 90 cm from the observer scaled down in size to match the appearance of near stimuli (far downscaled).

Figure 3A depicts individual thresholds for discerning orientation changes between successive near stimuli and between successive far stimuli. As shown, all participants were able to discern smaller orientation changes between successive far stimuli. Figure 3C depicts normalized thresholds averaged across participants, determined by expressing individual thresholds for far, near upscaled, and far downscaled stimuli in proportion to near thresholds. Values less than 1 indicate heightened sensitivity relative to standard-sized near stimuli, whereas values greater than 1 indicate reduced sensitivity.

We found that participants were more sensitive to orientation changes between successive far stimuli (apparently located at a viewing distance of 90 cm) than they were to changes between physically identical near stimuli (apparently located at a viewing distance of 45 cm; normalized far single-sample $t_5 = 3.72$, $p = 0.014$; see Figure 3C). Because of the illusory difference in size between near and far stimuli, these data suggest a close relationship between sensitivity to orientation changes and apparent, as opposed to just physical, size.

Observers were also more sensitive to orientation changes between successive near upscaled stimuli than they were to changes between physically smaller near stimuli (normalized near upscaled single-sample $t_5 = 4.31$, $p = 0.018$; see Figure 3C). However, observers were equally sensitive to orientation changes between successive far downscaled stimuli and near stimuli (normalized far downscaled single-sample $t_5 = 0.53$, $p = 0.62$; see Figure 3C) despite the physical size difference between these stimuli. These data suggest that the variations in orientation change sensitivity that we observed were predominantly driven by improved sensitivity for apparently and physically larger inputs relative to standard-sized near stimuli. Overall, our manipulations of physical size induced a larger overall variation in sensitivity (a proportional variation from 1.06 for far downscaled to 0.64 for near upscaled) than did our manipulation that induced an illusory size change (a proportional sensitivity of 0.84 for far stimuli relative to physically identical near stimuli).

The judgments reported thus far have concerned clearly visible stimulus properties. We wanted to determine whether

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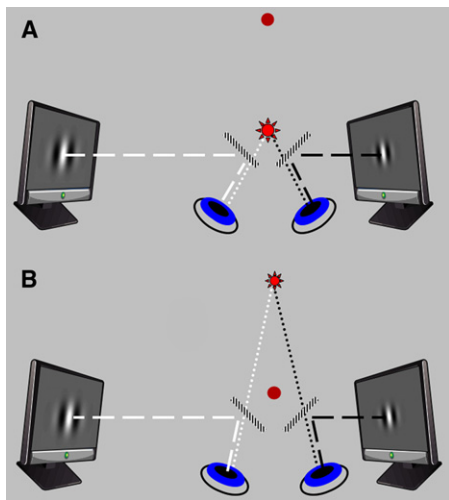


Figure 1. Depictions of the Apparatus Used in the Experiments

In the preliminary size illusion experiment and in calibration procedures before each run of trials, two diodes served as fixation points to guide eye vergence. These were positioned 45 cm (near fixation point) and 90 cm (far fixation point) directly in front of the observer and were only visible in the darkened room when lit. Participants viewed the lit diodes through half-silvered mirrors, which permit the observer to simultaneously see the scene beyond the mirror and the mirror reflection. Test images were presented via two monitors, positioned to the left and right of the observer and visible via the half-silvered mirrors. One of the monitors was located at the same optical distance as the near fixation point while the other was positioned at the same optical distance as the far fixation point. This ensured that during natural viewing, one of the two test images was focused when either fixation point was fixated.

the scaling operations triggered by illusory viewing distance changes would also impact on the ability to detect input. In this experiment, one of two otherwise clearly visible successive gray stimuli contained a slight sinusoidal modulation of luminance contrast. The other gray stimulus did not contain a contrast modulation (see Figure 2B, Experimental Procedures, and Supplemental Experimental Procedures for further details). By manipulating the amplitude of contrast modulations on a trial-by-trial basis, we were able to determine contrast detection thresholds, which are estimates of the minimal detectable luminance contrast modulation. We did so for near, far, near upscaled, and far downscaled stimuli. Individual contrast detection thresholds for near and far stimuli are depicted in Figure 3B. Again, we normalized individual thresholds for far, near upscaled, and far downscaled stimuli by expressing these as proportions of individual near thresholds. These normalized thresholds, averaged across participants, are depicted in Figure 3D.

We found that participants were equally sensitive to low-contrast modulations of near and far stimuli (normalized far single-sample $t_5 = 0.96$, $p = 0.38$; see Figure 3D), even though the latter appeared larger in size. Observers were less sensitive to modulations of far downscaled stimuli relative to modulations of standard-sized near stimuli (normalized far downscaled single-sample $t_5 = 3.54$, $p = 0.02$; see Figure 3D). This shows that a physical reduction in size impaired sensitivity for detecting contrast modulations. However, a physical increase in size did not enhance sensitivity (normalized near upscaled single-sample $t_5 = 1.32$, $p = 0.25$; see Figure 3D). Overall, this pattern of results is consistent with a close

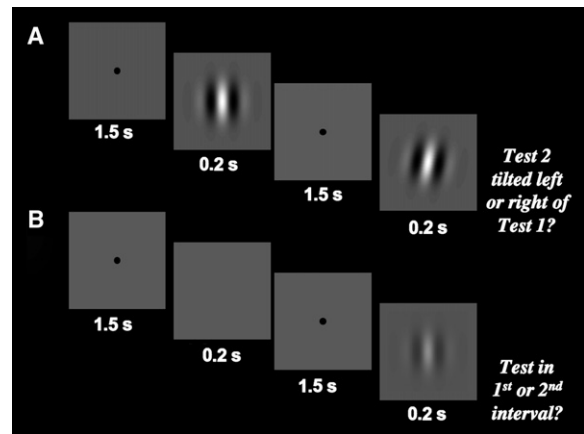


Figure 2. Depictions of Trial Sequences

(A) Depiction of the trial sequence from experiment 1: tilt discrimination.
(B) Depiction of the trial sequence from experiment 2: contrast detection.

relationship between contrast sensitivity and physical retinal image size, as opposed to apparent size.

Our data suggest that the scaling operations triggered by illusory viewing distance changes can shape sensitivity for slight orientation changes between successive clearly visible stimuli. However, they had no evident impact on the ability to detect low-contrast modulations of visible input. Because our manipulation of apparent viewing distance involved changing the vergence angle of the eyes, it was possible that these data were shaped by accommodation errors, which can degrade retinal images and impair visual sensitivity [9]. Previous studies have suggested that this can create a false impression, wherein the ability to detect low-contrast inputs seems to scale with apparent size when in fact the sensitivity variation is due to optical artifacts [10–12]. We therefore reexamined sensitivity for orientation changes but adopted a standard control for accommodation effects: participants viewed stimuli through pinhole apertures (see Supplemental Experimental Procedures for further details). Data from this accommodation control experiment revealed that participants were still more sensitive to orientation changes between far stimuli than they were to changes between physically identical near stimuli (normalized far single-sample $t_3 = 3.66$, $p = 0.035$; see Figure 4).

In all experiments reported thus far, stimuli were either vertical or only slightly tilted from vertical. These data could therefore be shaped by neural adaptation to vertical inputs. To assess whether this was a critical factor for improving sensitivity to orientation changes, we examined sensitivity for orientation changes between successive near and far stimuli but avoided orientation-specific adaptation by randomizing the orientation of the initial stimulus in each trial (see Supplemental Experimental Procedures for further details). Again, participants were more sensitive to changes between far stimuli than they were to changes between near stimuli (normalized far single-sample $t_3 = 10.76$, $p = 0.002$; see Figure 4).

Our data reveal a hitherto unrecognized influence on visual sensitivity. Participants were more sensitive to orientation changes between clearly visible stimuli when the stimuli appeared to be larger as a result of their apparent position in depth, 90 cm in front of the observer as opposed to 45 cm. These data therefore establish a link between visual sensitivity

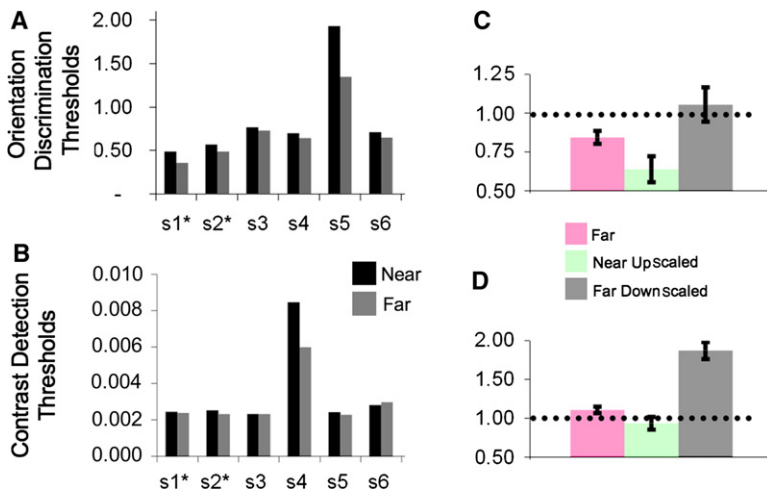


Figure 3. Bar Plots Depicting the Results of Experiments 1 and 2

(A) Bar plot depicting individual orientation discrimination thresholds from experiment 1. Subjects s1 and s2 are the authors. (B) Bar plot depicting individual Michelson luminance contrast detection thresholds from experiment 2. (C) Bar plot showing normalized orientation discrimination thresholds from experiment 1, averaged across participants. Normalized data are shown for far, near upscaled, and far downscaled stimuli. The dotted horizontal line marks a value of 1, which indicates equal sensitivity relative to near stimuli. (D) Bar plot showing normalized luminance contrast detection thresholds from experiment 2, averaged across participants. Error bars in (C) and (D) indicate \pm one standard error of the mean.

and the sensory scaling processes triggered by apparent viewing distance changes.

Our results concerning luminance contrast sensitivity were markedly different. The introduction of an illusory size change had no discernable impact on the ability to detect slight contrast modulations of otherwise clearly visible stimuli. However, a physical reduction in size (far downsampled data; see Figure 3D) did impair sensitivity, even though these physically smaller stimuli were matched in apparent size to the physically larger near stimuli. These data therefore not only reconfirm long-established links between the physical dimensions of retinal images and the ability to detect low-contrast inputs [13, 14] but also reveal that this relationship can hold in the absence of any apparent size differences.

It has been proposed [14–16] that the visibility of sinusoidal luminance modulations is governed by a critical ratio relating the area of primary visual cortex used to encode input to the spatial frequency of the luminance modulation. Physical viewing distance changes induce proportional and inverse changes in image size and spatial frequency. Because retinal image size is the primary determinant of the area of primary visual cortex used to encode input, physical viewing distance changes do not change the critical ratio, potentially explaining why threshold contrasts can be invariant across large viewing distance changes [15, 16] and changes in vergence [10, 11]. Our data concerning the effects of apparent viewing distance changes on threshold contrast are consistent with these proposals. However, our data concerning sensitivity to orientation changes suggest that judgments concerning clearly

visible stimulus properties might be subject to a more complex relationship.

One of the fundamental features of human vision is the lawful mapping between retina and visual brain regions. This allows us to predict, based on the size and locations of retinal images, where visually evoked brain activity will occur and how far across the cortex it will extend [17–19]. However, recent brain imaging studies have established that the spread of activity across visual brain regions can be modulated by illusory size changes [4–6]. These observations have been supported by convergent behavioral evidence concerning sensory interactions between successive inputs [20]. Our data here suggest that depth-size scaling operations, which can influence the spread of activity across visual brain regions [4–6], also shape sensitivity to changes between clearly visible inputs but do not enhance the ability to detect slight contrast modulations.

One plausible interpretation of our results would be that depth-size scaling operations only modulate the spread of cortical representations associated with clearly visible stimulus features. For our data to be consistent with accounts linking sensitivity to a critical ratio involving primary visual cortical area and waveform spatial frequency [14–16], there must also be a dissociation. For instance, waveform spatial frequency sensitivity might be determined entirely by the physical properties of retinal input, whereas size-depth scaling operations modulate the area of primary visual cortex used to encode clearly visible stimulus features [4–6]. This would allow for a sensitivity modulation for clearly visible inputs, due to illusory size-depth relationship changes, which have no impact on the ability to detect low-contrast stimuli.

These suggestions are inconsistent with an automatic, apparent-viewing-distance-contingent modulation of all visual input. Instead, sensitivity modulations are more likely to be triggered for stimulus features that exceed a sensory threshold. Furthermore, we anticipate that the processes responsible for this sensitivity modulation will involve interactions between lower-level visual brain structures, implicated in fine spatial resolution judgments [21], and higher-level visual brain regions, which encode information concerning apparent viewing distance [22, 23].

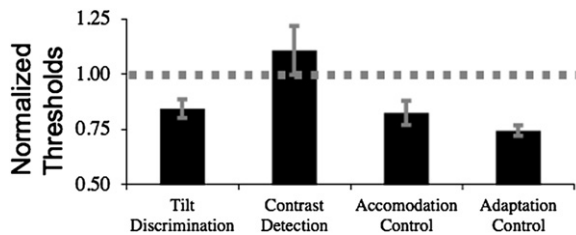


Figure 4. Bar Plots Depicting Normalized Results from Experiments 1–4
Normalized far orientation discrimination thresholds from experiments 1 (tilt discrimination), 2 (contrast detection), 3 (accommodation control), and 4 (adaptation control). The dotted horizontal line marks a value of 1, which indicates equal sensitivity relative to near stimuli. Data are averaged across participants. Error bars indicate \pm one standard error of the mean.

Experimental Procedures

Experiments were conducted in a darkened room. Visual stimuli were generated with MATLAB software in conjunction with the Psychophysics Toolbox

[24, 25] and presented on two Samsung Syncmaster 750 S monitors (1024 × 768 resolution, 75 Hz refresh rate) located to the left and right of the observer and viewed via half-silvered front surface mirrors. One of the two monitors was located at an optical distance of 45 cm whereas the other was 90 cm from the observer (see Figures 1A and 1B). All stimuli were shown on both monitors, and the two stimulus images were physically scaled so that they were matched in terms of retinal image size.

Full procedural details concerning each of the experiments are presented in the [Supplemental Experimental Procedures](#) available online.

Supplemental Information

Supplemental Information includes Supplemental Experimental Procedures and can be found with this article online at [doi:10.1016/j.cub.2010.02.068](https://doi.org/10.1016/j.cub.2010.02.068).

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