Illusory bending of a rigidly moving line segment: Effects of image motion and smooth pursuit eye movements

Lore Thaler Department of Psychology, The Ohio State University, Columbus, OH, USA

James T. Todd Department of Psychology, The Ohio State University, Columbus, OH, USA

Miriam Spering Psychologisches Institut, Justus-Liebig-Universität, Gießen, Germany

Karl R. Gegenfurtner Psychologisches Institut, Justus-Liebig-Universität, Gießen, Germany

Four experiments in which observers judged the apparent "rubberiness" of a line segment undergoing different types of rigid motion are reported. The results reveal that observers perceive illusory bending when the motion involves certain combinations of translational and rotational components and that the illusion is maximized when these components are presented at a frequency of approximately 3 Hz with a relative phase angle of approximately 120°. Smooth pursuit eye movements can amplify or attenuate the illusion, which is consistent with other results reported in the literature that show effects of eye movements on perceived image motion. The illusion is unaffected by background motion that is in counterphase with the motion of the line segment but is significantly attenuated by background motion that is in-phase. This is consistent with the idea that human observers integrate motion signals within a local frame of reference, and it provides strong evidence that visual persistency cannot be the sole cause of the illusion as was suggested by J. R. Pomerantz (1983). An analysis of the motion patterns suggests that the illusory bending motion may be due to an inability of observers to accurately track the motions of features whose image displacements undergo rapid simultaneous changes in both space and time. A measure of these changes is presented, which is highly correlated with observers' numerical ratings of rubberiness.

Keywords: motion perception, motion integration, bending motion, nonrigid motion, rigid motion, smooth pursuit eye movements

Citation: Thaler, L., Todd, J. T., Spering, M., & Gegenfurtner, K. R. (2007). Illusory bending of a rigidly moving line segment: Effects of image motion and smooth pursuit eye movements. *Journal of Vision, 7*(6):9, 1–13, http://journalofvision.org/7/6/9/, doi:10.1167/7.6.9.

Introduction

Since the seminal work of Wallach (1935), it has long been recognized that the motions of smooth contours can be perceptually ambiguous. Consider, for example, the rotating ellipse that is presented in Auxiliary Movie 1. Although the ellipse is rotating rigidly in the image plane, it appears perceptually to be undergoing a nonrigid deformation (see Hildreth, 1984; Weiss & Adelson, 2000). The reason for this effect is that all points along the contour are visually indistinguishable so that it is not possible to measure the component of motion that is parallel to the contour at any given location. If, however, the pattern contains some distinct identifiable points, as in Auxiliary Movie 2, then the unambiguous motions of those features can constraint the interpretation of the contour motion, resulting in the perception of rigid rotation.

The experiments described in Wallach's (1935) original monograph all involved the translatory motions of straight-line contours. The perceptual ambiguity in that case is typically quite constrained. Although observers may perceive an illusory direction of motion, the moving contour always appears rigid. Indeed, this should not be surprising, given that the collinearity of the contour is never altered.

There is an interesting parlor demonstration called "the rubber pencil illusion" that is especially compelling because it violates this basic intuition. If a pencil is held loosely off center and wiggled up and down, it can appear to undergo a nonrigid bending motion (see Figure 1), although the pencil remains physically straight at all times. Note that this illusion occurs despite the presence of trackable features at the endpoints of the moving pencil and the absence of any contour curvature in its optical projection.

doi: 10.1167/7.6.9 Received August 24, 2006; published April 20, 2007 ISSN 1534-7362 © ARVO

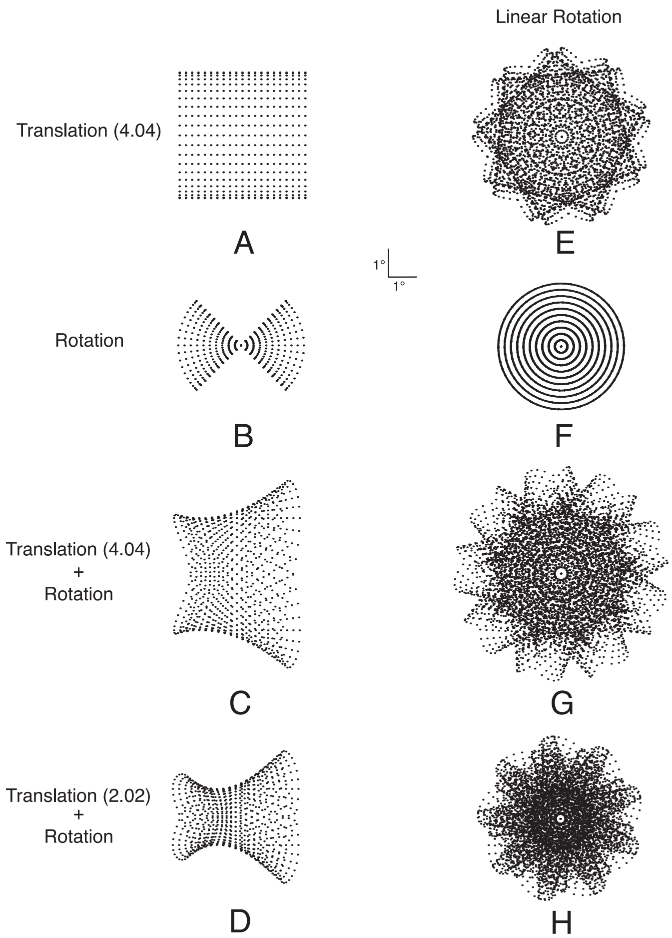

Figure 3. Static representations of the motion displays used in Experiment 1. Each panel on the left depicts a superposition of the 40 discrete frames of a particular motion sequence. Panels on the right show the motion pattern that was created by combining the pattern on the left with a linear rotation around the origin at a constant angular velocity over 360 discrete frames.

that describe the stimulus motion are shown in the Appendix.

Procedure

At the beginning of an experimental session, the rubber pencil illusion was demonstrated to the observer using an actual pencil. All observers spontaneously reported the percept of bending. The experimenter then read a standardized script in which the basic design of the experiment was described. On each trial, a motion display was presented on a computer monitor directly in front of the observer. A second monitor located off to the side displayed a numerical rating between 0 and 10 that could be adjusted by clicking the right and left buttons on a handheld computer mouse. Observers were instructed to rate the rubberiness of each motion pattern on this scale such that higher ratings indicated greater degrees of perceived rubberiness. A base rating of 0 was displayed at the beginning of each trial. When observers were satisfied with their setting, they proceeded to the next trial by hitting "enter" on the computer keyboard. It was possible to move backward in the sequence to revise settings, and many observers made use of this option to compare stimuli prior to rating them. Displays were presented in a random sequence for each observer. During debriefings, all observers reported that they felt confident in their settings and that various displays appeared nonrigid to them.

Observers

The displays were rated by eight observers, including one of the authors (J. T.) and seven others who were naïve to the purposes of the experiment. All observers had either normal or corrected-to-normal vision.

Results and discussion

Because observers were not required to use the full range of the rating scale, the results were normalized for each observer by dividing every rating by the maximum rating assigned by that observer. Figure 4 shows average normalized rubberiness rating across all observers for each of the different experimental conditions. Error bars denote standard errors of the mean within each group.

It is important to note when evaluating these results that Displays A–D are a near replication of those used by

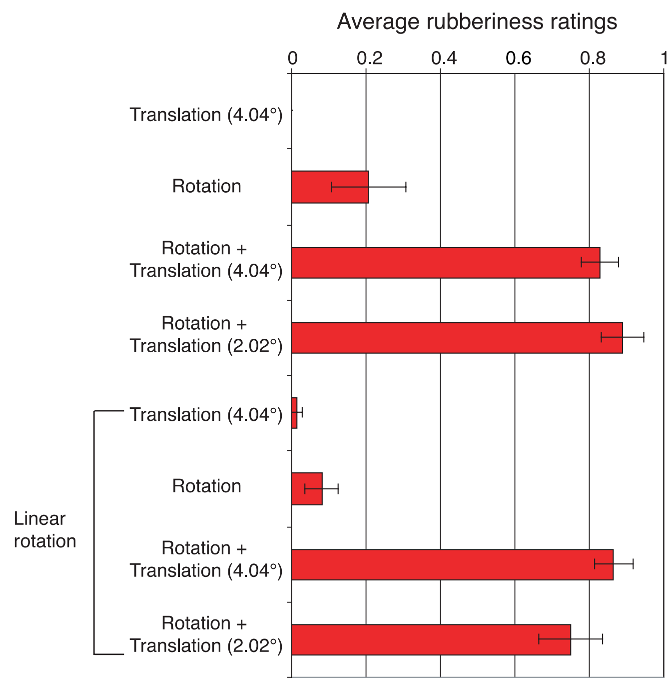

Figure 4. The average rubberiness ratings obtained in Experiment 2 for the different experimental conditions illustrated in Figure 3.

to go back through the stimulus sequence and to rate each motion pattern they had created with respect to its apparent bending on a rating scale of 0 to 10, as in Experiment 1. Each of the nine relative phase angles was presented twice in random order. In one presentation, stimulus motion was initiated with a speed of 3.75 Hz, and in the other, it was initiated with a speed of 1.5 Hz. The procedure was identical in the phase condition except that the observers adjusted the relative phase of the translational and rotational components rather than their speeds.

Observers

The displays were evaluated by eight observers, including two of the authors (L. T. and J. T.) and five others who were naïve to the purposes of the experiment. All observers had either normal or corrected-to-normal vision.

Results and discussion

The contour plot presented in the top panel of Figure 5 shows the frequency of maximum rubberiness settings for

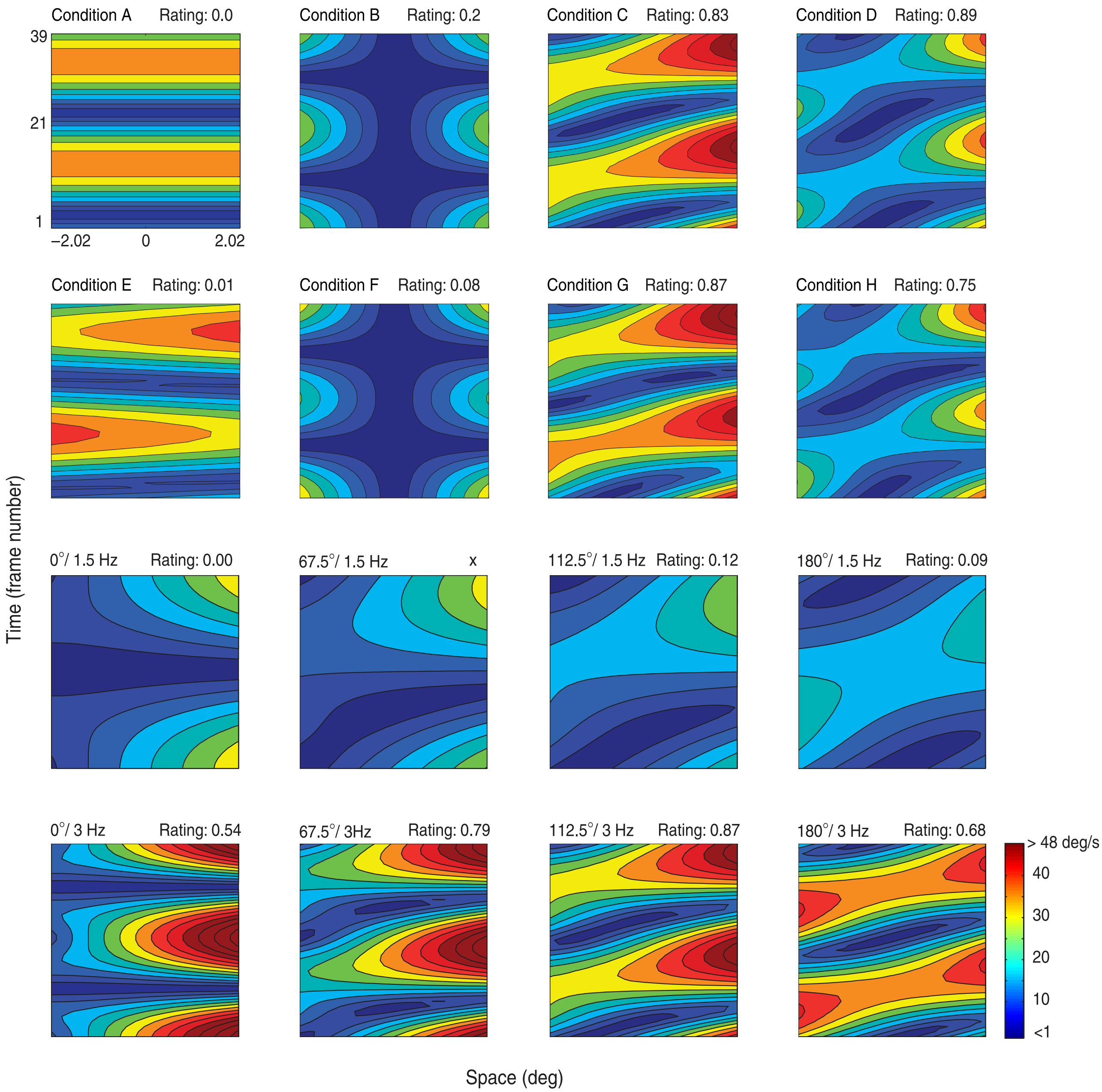

Figure 6. Contour plots of displacements for selected motion patterns from Experiments 1 and 2 at each position along the line segment (indicated on the horizontal axis) at each moment in time (indicated on the vertical axis). The text above each panel specifies the experimental condition and average judged rubberiness. Crosses indicate that a condition was not selected (and therefore not rated) by any observer.

of 1,024 (H) × 768 (V) pixels. The active display area subtended 39 × 29.3 cm, and the display was positioned at a distance of 47 cm from the observer.

Eye-movement recording

Eye position signals were recorded with a head-mounted, video-based eye tracker (EyeLink II; SR Research Ltd., Osgoode, Ontario, Canada) and were sampled at 250 Hz. The apparatus was calibrated at the beginning of the main experiment by instructing the observer to fixate single dots that appeared successively at nine different positions on the monitor. Based on the results of this calibration, the better eye was chosen automatically by the system, and eye position was recorded from this eye. Observers were seated with their heads stabilized with a chin rest. They viewed the display binocularly through natural pupils. A PC controlled stimulus display and data collection.

Stimuli

Each stimulus contained a smooth black line segment moving in front of a homogeneous, gray background (mean luminance 39 cd/m^2). The length of this line was 4.04° and its width was 0.1°. All of the displays included a rotary oscillation, in which the line segment rotated back and forth through an angle of 90° at a rate of 2.5 Hz. On half the trials, this rotary oscillation was the only source of distal motion. On the remaining trials, an additional component of motion was added, in which the center of the line segment was translated along an elliptical orbit around the center of the display screen at a rate of 0.83 Hz. The horizontal and vertical axes of the elliptical trajectory subtended 8.08° and 4.84°, respectively. Both of these distal motion conditions were observed with the eyes fixated on a stationary point and with the eyes tracking a moving fixation point along an 8.08° × 4.84° elliptical trajectory. These different combinations of distal and eye motion resulted in four basic experimental conditions that are illustrated in Figure 8. The equations used to generate these motions are given in the Appendix.

Procedure

Each trial began with a stationary visual target whose diameter subtended 0.5° of visual angle, and the color of this target indicated whether the upcoming motion display would include a stationary (blue) or moving (red) visual target. Observers initiated a trial by pressing an assigned button. The EyeLink II system then performed a drift correction to correct for shifts of the head-mounted tracking system. Once this was achieved, the stimulus presentation was initiated after a random time interval between 200 and 400 ms. On trials that required smooth pursuit eye movements, the fixation point began to move

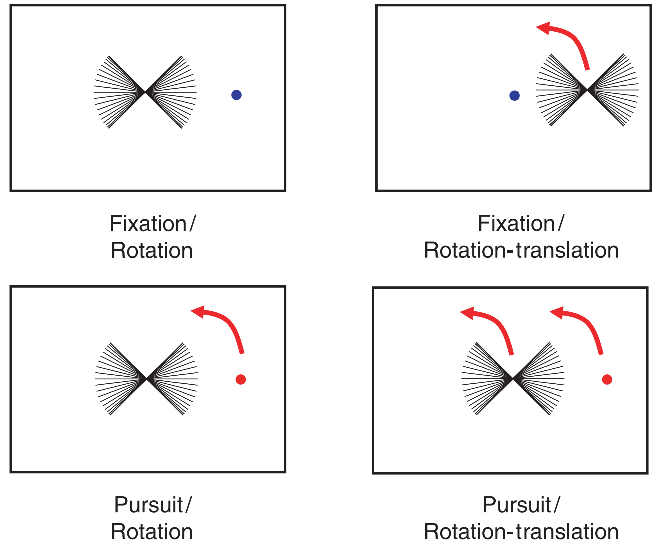

Figure 8. Illustrations of motion displays used in Experiment 3. The rotational motion of the line segment is represented by superimposing the 40 discrete frames of a rotational motion sequence. Translational, elliptical motion of the line segment or/and the eye is indicated by arrows. Dots illustrate the visual target in fixation (blue-colored target) or pursuit (red-colored target) conditions.

as soon as the line segment appeared. After 2.4 s, the display motion was terminated, and observers rated its rubberiness on a rating scale from 0 to 4 by pressing assigned keys on the keyboard. Stimuli were presented in blocks of 20 trials containing five repetitions of the four experimental conditions. An experimental session included six blocks, the first of which was discarded as practice.

Observers

Ten observers participated in the experiment, including one of the authors (M. S.) and nine naïve observers who were selected from the observer pool at the University of Giessen, Germany, where the experiment was conducted. Observers were contacted via telephone and were paid for their participation. All observers had normal or corrected-to-normal vision and were highly trained in smooth pursuit tasks.

Analysis of eye movements

To compare perception of rubberiness in the different pursuit and fixation conditions, we had to ensure that observers had followed our instructions concerning eye movements and, furthermore, that eye movements were comparable in the pursuit and fixation conditions. Eye movements were analyzed in two steps. The first step was designed to remove any saccades from the overall position traces as described by Spering, Kerzel, Braun, Hawken, and Gegenfurtner (2005). Any movements that exceeded

15°/s in the fixation conditions or 45°/s in the pursuit conditions were considered as saccades and excluded from subsequent analyses. The remaining position traces were then smoothed, and the average eye velocity was divided by the average target velocity (17.19°/s) to determine the perceptual gain for each trial. If the resulting gain was above 0.23 for the fixation conditions or below 0.77 for the pursuit conditions, the trial was considered invalid. Trials were also considered invalid if observers blinked during the 2.4-s stimulus presentation.

Based on these criteria, one observer was excluded from further analysis because low pursuit gain resulted in too few valid trials in pursuit conditions ($n < 5$). Across the remaining nine observers, 10.4% of all trials ($n = 94$) were excluded from further analyses, all of them pursuit trials. Average eye-movement gain in the two pursuit conditions was 0.89 and 0.90, respectively (between-observer SD = 0.07 and 0.06, respectively). Average eye-movement gain in both fixation conditions was 0.09 (between-observer SD = 0.02 in both conditions). Only numerical ratings obtained in valid trials were considered for further analysis.

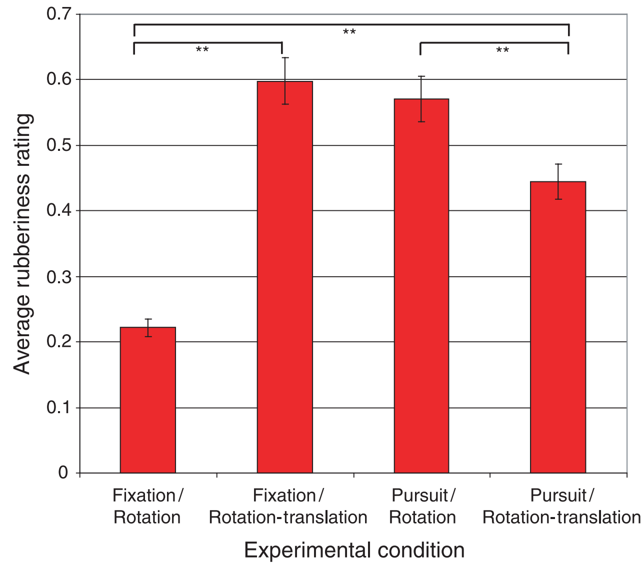

Figure 9. The average rubberiness ratings obtained in Experiment 3. **$p < .01$.

Results

The normalized ratings for each condition averaged over observers are presented in Figure 9. Error bars indicate standard error of the mean within each group. An analysis of variance revealed that there were significant main effects of distal motion, $F(1, 8) = 10.07$, $p < .05$, and eye motion, $F(1, 8) = 11.78$, $p < .01$, and a significant interaction, $F(1, 8) = 24.84$, $p < .001$. Additional post hoc paired-sample t tests (two sided) were performed to compare individual pairs of conditions. Significance is indicated in Figure 9 by asterisks.

If the apparent rubberiness of the displays were based entirely on the distal motion patterns, then there should be no significant differences between the fixation and pursuit conditions. If, on the other hand, the apparent rubberiness of the displays were based entirely on the retinal motion patterns, then the fixation/rotation and pursuit/rotation–translation conditions should both produce low rubberiness ratings, and the pursuit/rotation and fixation/rotation–translation conditions should both produce high rubberiness ratings. It is clear from Figure 9 that neither of these hypotheses can provide a complete account of the data, although retinal motion seems to be the predominant factor that influenced observers' judgments. Note, for example, that the pursuit/rotation and fixation/rotation–translation conditions both produced high rubberiness ratings, as would be expected based on a pure retinal motion hypothesis. This finding suggests that when a smooth pursuit eye movement is independent of a distal object's motion, then the eye movement is not discounted in the perceptual analysis of that motion (see also Brenner & van den Berg, 1994). However, when the eye movements tracked the motion of a distal object in the pursuit/rotation–translation condition, the results indicate that they were partially discounted. That is to say, the apparent rubberiness of the pursuit/rotation–translation displays was halfway between what would be expected from a pure retinal motion hypothesis and a pure distal motion hypothesis. Taken together, the results suggest that extra retinal signals are ignored when the eyes move on a different trajectory as the target but that they are partially accounted for when the line segment and the eye follow the same elliptical trajectory (see also Brenner & van den Berg, 1994).

It is important to note that pursuit gain was comparable in the two pursuit conditions. Thus, the data provide strong evidence that similar pursuit trajectories have different effects on the perception of bending motion, depending upon the direction of the pursuit trajectory with respect to the target trajectory. It could be argued that the retinal motion patterns in the pursuit and fixation conditions were not entirely equivalent because the pursuit conditions produced retinal motion at the edges of the monitor whereas the fixation conditions did not. However, it is not obvious how this would explain the differential effects of pursuit in the two distal motion conditions.

It is also interesting to note that the results of the present experiment have been replicated using dotted line segments. This replication was conducted at the Ohio State University on the apparatus described in Experiment 1 with the same participants as in Experiment 1. Although observers were instructed to pursue or fixate in the appropriate conditions, we did not confirm through eye-movement recordings the extent to which they complied with those instructions. Nevertheless, the results obtained

Procedure

Each trial began with a fixation target subtending 0.5° of visual angle that was located 2.6° above the center of the display. Observers initiated a trial by pressing an assigned button. The EyeLink II system then performed a drift correction to correct for shifts of the head-mounted tracking system. Once this was achieved, the stimulus presentation was initiated after a random time interval between 200 and 400 ms. Each trial included two different motion displays in successive 2-s intervals with a 0.5-s separation period. Observers were instructed to remain fixated on the target during the entire display period. Once the display was terminated, observers were required to judge which interval appeared more "rubbery" by pressing an appropriate key on the computer keyboard. They were instructed to judge only the motion of the central line segment and to ignore the background. Stimuli were presented in blocks of 42 trials containing seven repetitions of the seven experimental conditions. An experimental session included four blocks, the first of which was discarded as practice.

Observers

Ten observers with normal or corrected-to-normal vision participated in the experiment. All participants were experienced psychophysical observers and were selected from an observer pool at the University of Giessen, Germany. Observers were contacted via telephone and were paid for their participation.

Analysis of eye movements

To compare perception of rubberiness in the different conditions, we had to ensure that observers had fixated properly during the 4.5-s stimulus presentation. The analysis of eye movements differed from the one described for Experiment 3 in that we calculated the average eye velocity in degrees per second as a measure of fixation stability instead of relative gain. Eye velocity during both 2-s intervals was required to be less than 3°/s to be considered valid fixation. Otherwise, the trial was excluded from further analysis. Trials were also excluded from further analysis if the observer blinked during the 4.5-s stimulus presentation. Based on these criteria, 14.76% (n = 186) of all trials were excluded from further analyses across observers. Eye velocity was comparable across observers and experimental conditions for the remaining trials (average eye velocity = 1.83°/s, median = 1.85°/s, SD = 0.22°/s, range = 0.81°/s). As in Experiment 3, we also used an alternative analysis of eye movements that relied on a position criterion to assess fixation stability, with equivalent results.

Results

Table 1 shows the pattern of results combined over all observers for all of the possible pairwise comparisons among the different conditions. Values in each cell show the probability that the condition labeled in the column was rated as more rubbery than the condition labeled in the row. Values in parentheses indicate the number of trials over which each probability was computed.

To provide a summary of the data that takes into account possible differences between observers, we calculated for each observer and each condition the probability of that condition to be judged more bending over all its pairwise comparisons. Figure 11 shows the probability of each condition to be judged more rubbery over all of its possible pairwise comparisons averaged across observers. Error bars denote standard errors of the mean within each group, and asterisks indicate significant differences between conditions assessed via paired-sample t test (two sided). Note in the figure that when the background moves in counterphase with the moving line segment, it has no discernable effect on apparent rubberiness relative to the bending standard condition with a homogeneous background. However, if the line segment is presented against a static textured background or if the background motion is identical to that of the line segment, then the perception of rubberiness is intermediate between

	Rigid standard	Rectangle in-phase	Texture in-phase	Texture static	Bending standard	Texture off-phase	Rectangle off-phase
Rigid standard	X	.86 (50)	.98 (51)	.96 (48)	.96 (45)	.98 (50)	.98 (46)
Rectangle in-phase		X	.82 (50)	.72 (58)	.84 (49)	.85 (54)	.93 (54)
Texture in-phase			X	.55 (53)	.70 (53)	.73 (51)	.68 (53)
Texture static				X	.59 (56)	.57 (51)	.63 (51)
Bending standard					X	.45 (49)	.49 (47)
Texture off-phase						X	.51 (55)
Rectangle off-phase							X

Table 1. Results from Experiment 4. Each cell represents the probability of the condition denoted in the column to be judged more rubbery than the condition denoted in the row. Values in parentheses represent the number of pairwise comparisons used to compute probabilities in each cell.