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The Visual Perception of Elasticity

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THE VISUAL PERCEPTION OF ELASTICITY

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Directed by: J. Farley Norman, Ph.D., Dan Roenker, Ph.D., and Kelly Madole, Ph.D.

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Two experiments were designed to evaluate human sensitivity to elasticity. Elastic objects bend when a force is applied to them. Observers saw two computer-generated bending rods (defined by the motions of 50 dots) on any given trial and were required to judge which rod was more flexible. Elasticity difference thresholds were calculated for each observer for each of three bending conditions. The rods bent in a plane that was either frontoparallel or oriented 42.5 or 85 degrees from frontoparallel. The results showed that observers could precisely discriminate between bending rods of different elasticities, independent of whether the bendings occurred in the frontoparallel plane or in depth. To rule out the possibility that the ability to judge bending motion was based on the ability to judge 2-dimensional (2-D) speed a second experiment was conducted to obtain difference thresholds for 2-D speed. The observers' speed discrimination thresholds were not positively correlated with their elasticity discrimination thresholds, which suggests that the observers' ability to judge bending motion was not based on their capability to discriminate differences in speed.

Chapter 1

Introduction

In ordinary environments, whether outdoor or indoor, the visual systems of human and animal observers must successfully cope with a wide variety of nonrigid motions. Common examples of nonrigid motions include trees and shrubs blowing in the wind, the biological motions produced by animals and people, and nonrigid motions of 2-dimensional (2-D) surfaces (such as the rustling of flags). These types of nonrigid motions are as common as rigid forms of motion, such as the translation exhibited by cars driving along a highway.

In real-life circumstances, the human visual system must be able to discriminate between rigid and nonrigid forms of motion and apply the correct type of analysis in each case. Without the ability to do this, even something as simple as a handshake would be challenging, because of the nonrigid movements of the other person's arm. Walking in a crowd would be difficult without being able to correctly interpret the biological motion of those around. Our social interactions would become much more difficult without the ability to perceive nonrigid facial movements, such as smiling and the movements of the eyebrows. Without the ability to perceive nonrigid motion, a surfer would not be able to ride a wave.

Much is known about the human perception of rigid motion (e.g., Wallach & O'Connell, 1953, Braunstein, 1962; Braunstein & Andersen, 1984; Lappin, Norman, & Mowafy, 1991; Norman & Lappin, 1992). Wallach and O'Connell conducted research in perceived 3-dimensional (3-D) structure from motion using moving shadows. Wallach and O'Connell cast shadows of a 3-D rotating object onto a flat projection screen. The observers only viewed the resulting deforming 2-D shadows (not the actual 3-D object) using one eye; nevertheless, they perceived a rigidly rotating object. This ability to perceive 3-D shape from deforming 2-D projected stimuli was termed the kinetic depth effect.

Braunstein (1962) manipulated the number of dots and the amount of perspective in a rotating (rigid form of motion) kinetic depth effect pattern to study their effects on depth perception. He found that the participants perceived more depth as the number of dots in the stimulus increased. As the perspective increased, the perception of depth also increased, but to a lesser degree.

Lappin, Norman, and Mowafy (1991) examined rotation, translation, expansion, and shear in a study that examined the detectability of geometric structure in rapidly changing dot patterns. The observers were asked to discriminate between rigid and nonrigid motions. For all four of the types of motion the observers' performance increased as the amount of motion was increased. The observers were able to successfully discriminate between rigid and nonrigid forms of motion. Norman and Lappin (1992) evaluated the detectability of surface curvature that was defined by motion. Their curved surfaces were generated by the kinetic depth effect (i.e., by rigid 3-D rotations). The participants were sensitive to very small differences in the curvature of the surfaces.

A significant amount of research has also investigated the perception of nonrigid biological motions (Johansson, 1973; Norman, Payton, Long & Hawkes, 2004; Pavlova, Krägeloh-Mann, Skolov, & Birbaumer, 2001). Johansson (1973, 1976) pioneered the investigation of biological motion. He attached ten to twelve small lights to the joints of a model, who then performed various activities in the dark. Observers who then viewed the nonrigid dot motions were able to correctly recognize whether the model was walking, running, climbing, dancing, etc. Johansson (1976) later extended his investigations of biological motion by examining how much time is needed for an observer to correctly perceive and identify various types of biological motion. His observers were able to discriminate biological motions at a 100 percent level of accuracy with only a 200-msec stimulus duration. Johansson's early findings stimulated further work on biological motion.

Norman, Payton, Long, and Hawkes (2004) investigated aging and the perception of biological motion using Johansson's (1973) work as a basis. The observers viewed nonrigid motions that were generated by a human model wearing 13 halogen light bulbs while walking, jogging, and skipping. The participants were required to discriminate between the three activities. The older group's performance (mean age was 73 years) was comparable to that of the younger group (mean age was 20 years) for stimulus durations of 400 ms. The older group's performance deteriorated for stimulus durations of 240 and 120 ms, but they still performed well above chance. These experiments showed that the ability to perceive nonrigid biological motions is relatively well preserved across the lifespan.

Pavlova, Krägeloh-Mann, Skolov, and Birbaumer (2001) tested children's ability to recognize the biological motions of a human, a dog, and a bird depicted in point-light displays like those used by Johansson (1973). The participants were able to correctly identify the motions, but were unable to recognize static images. This study showed that

3 year olds were able to discriminate whether the forms were human or nonhuman, while a 5 year-old's ability to recognize the motions was the same as an adult's. The work of Pavlova et al. (2001) and Norman, Payton, Long, and Hawkes (2004) shows that the ability to perceive nonrigid biological motion is mature at five years of age and persists (with modest deficits) throughout the lifespan.

Past research indicates that rigid motions can appear nonrigid (Ishiguchi, 1988a, 1988b). For example, consider the rubber pencil illusion. This illusion occurs when a rigid rod or line of dots is wiggled -- this frequently produces the illusion of a rubbery or elastic motion. Ishiguchi (1988a) examined this phenomenon by presenting participants with lighted points that simulated the motion of a rigid rod in two experiments. In the first experiment, it was found that the number of dots and the phase differences in their motion affected the perceived elasticity of the rods. In a second set of experiments, Ishiguchi (1988b) further investigated the perception of elastic motion that occurs when observers view rigidly moving rods. The results of these later experiments showed that the orientations and positions of the rods were key factors in the perception of elasticity.

Other research has shown that people frequently misperceive nonrigid stimuli as if they were rigidly moving. Only a small amount of research has examined nonrigid motions other than biological motion (e.g. Norman & Todd, 1993; Todd, 1982). Todd (1982) analyzed the perception of rigid and nonrigid motion by presenting participants with five types of stimuli, one that simulated rigid rotation and four others that simulated various types of nonrigidity. The observers' task for each stimulus display was to indicate whether it appeared as rigid rotation or nonrigid deformation. Even without feedback, the participants were 95-99% correct in categorizing the rigid motion and three of the nonrigid motions. However, in one of the nonrigid conditions the percentage of correct responses was only 59-60%. The stimuli in this single condition were perceived as rigid, although they moved nonrigidly in reality. These displays simulated nonrigidity, because each of the moving points had a trajectory with a different eccentricity. Since these displays were frequently mistaken as rigid, human observers are apparently not sensitive to differences in trajectory eccentricity.

Norman and Todd (1993) conducted an experiment using figures composed of randomly oriented line segments that were similar to those used by Wallach and O'Connell (1953). Some of the figures were stretched nonrigidly in depth as they rotated at a constant speed. The participants rated the apparent rigidity of the figures. These nonrigidly stretching figures were mistakenly perceived as rigidly rotating objects that accelerated and decelerated over time.

Braunstein, Hoffman, and Pollick (1990) investigated the minimum number of views and points necessary for human observers to discriminate between rigid and nonrigid motion. In the rigid displays, all of the points rotated about the same axis. In the nonrigid displays, each point rotated about a different axis. For these displays, they found that four of the six observers could make the discrimination based on four points and two views, while the remaining two participants required five points and two views. In 1997, Domini, Caudek, and Proffitt replicated the results.

Researchers in vision have developed computational models that are able to recover 3-D shape and structure from both rigid and nonrigid forms of motion. Ullman's (1979) structure from motion model can extract the 3-D shape and structure of a rigidly moving object when given three orthographic views of four noncoplanar points.

Koenderink and van Doorn's model (1986) is able to recover 3-D shape and structure (up to a relief transformation) when given at least two views of seven nonrigidly moving points. The Koenderink and van Doorn model can successfully recover 3-D structure even when an object is undergoing severe bending.

Although computational models exist (e.g. Koenderink & van Doorn, 1986) that can successfully cope with bending, little research has been conducted on the human ability to perceive bending. Previous psychophysical research (e.g., Cutting, 1982; Jansson, 1977; Jansson & Johansson, 1973; Johansson, 1976; Jansson & Runeson, 1977) has shown that people can perceive the bending motions of elastic objects. For example, Cutting (1982) conducted an experiment that investigated the perception of the motion produced by trees and bushes. He created computer-generated stimuli that simulated the motions of swaying branches displayed against a solid black background (only points of light were visible, not the branches themselves); the observers were required to choose which drawing of tree or bush branch configurations matched those presented in the point light displays. It was found that human observers can effectively perceive at least the qualitative structure of a moving tree or bush.

Johansson (1964) presented to his observers a solid pattern of light that continuously changed from a square to a rectangle, and then back to a square. Many of the participants (graduate students, undergraduate students, and 10-11 year old children) perceived this stimulus as if it was either rigidly rotating in depth or nonrigidly folding or bending in depth (i.e., like a book opening and closing).

Jansson and Johannson (1973) showed that human observers successfully perceive the bending motions of a quadrangular shape. They obtained participants' classifications of six different quadrangles each undergoing a different type of 2-D transformation. The participants were asked to categorize the motion, and state whether each stimulus appeared to rotate, bend, stretch, etc. One of the stimulus types was perceived as bending by 29 out of the 30 participants.

In a very similar experiment, Jansson and Runeson (1977) used six quadrangles whose vertices exhibited various forms of relative motion, and then asked participants to classify the stimuli as rotating, bending, or stretching. One of the quadrangles was perceived as bending for all 30 out of 30 participants. The usefulness of these experiments is limited because the results only reveal that observers can perceive bending motions - they did not measure either the accuracy or the precision with which human observers perceive bending.

Jansson (1977) conducted the only quantitative assessment to date of how human observers perceive bending. In his experiment, participants viewed a bending line of points and were asked to adjust the curvature of a wire to match the curvature of the bending line. He found that his observers were able to accurately perceive the curvature of the bending line in many of the experimental conditions.

The purpose of the current study was to expand the small psychophysical literature on the perception of nonrigid motion by investigating bending. Although the bending of objects and surfaces is a common environmental event, essentially no other research has examined how human observers perceive it. To simulate 3-dimensional (3-D) bending in our experiments, we used a form of the kinetic depth effect (Wallach & O'Connell, 1953).

Twenty years ago Koenderink and van Doorn (1986) said, "…in daily life human vision copes easily and often with nonrigid deformations, apparently with a great deal of success. The exact measure of success is hard to quantify, though. Perhaps because of this difficulty, psychophysics has until now largely neglected this field" (p. 242). The current set of experiments ends this neglect by quantitatively evaluating human perceptual sensitivity to the elasticity of bending objects.

Chapter 2

Experiment 1

Observers

The observers were faculty (HFN & JFN) or students at Western Kentucky University (MJT, SER, & EYW). All observers had normal or corrected–to-normal visual acuity, and viewed the stimulus displays monocularly, using an eye patch to cover the eye of their choice. Two of the observers were highly experienced participants of psychophysical research (HFN & JFN).

Stimulus Displays

The orthographically projected stimulus display was a contour composed of fifty white points (each was two pixels wide) presented against a black background with a .2 cm space between each point. The method used to produce the bending motion was described by Craft, Payne, and Lappin (1986). In their research, Craft et al. used a parameter (K) to manipulate each bending rod's elasticity.

We used a two alternative temporal forced choice task, where two bending rods were sequentially presented on each trial. One rod had a standard elasticity value of .01 or .02 (this is the K parameter described by Craft et al., 1986), while the other rod had a test elasticity value that was 3, 9, or 15 percent greater or less than that of the standard. The rods bent in a plane that was rotated about a Cartesian horizontal axis 0, 42.5, or 85 degrees from fronto-parallel. The apparent motion sequences consisted of 60 individual frames. The initial frame that the observers saw on any given trial was randomly chosen. One end of each rod was anchored (i.e., it did not move) and a simulated force was applied to the other end of the rod. This produced a bending motion similar to that of a rigid cantilevered rod (Gordon, 1988). For each trial, two bending rods were presented for two seconds each. One hundred-seventy frames were presented during each temporal interval. The presentation of the two rods was separated by a one-second inter-stimulus interval. Eleven frames of the motion sequence for the .02 elasticity standard are shown in Figure 1. The first frame represents the most extreme upward deflection and the last frame represents the most extreme downward deflection.

Apparatus

The stimuli were generated by a dual-processor Apple G4 computer and displayed on a 22-inch Mitsubishi Diamond Plus 200 monitor. The stimulus displays were viewed at a distance of 100 cm. The observers responded by pressing different keys on the computer keyboard.

Procedure

Each observer made a total of 3600 judgments. On each of the 3600 trials, the observers were asked to judge whether the first or second bending rod was more elastic (i.e., which was more flexible).

There were a total of six experimental conditions formed by the combination of two standard elasticities and three orientations of bending planes. Six hundred bending stimuli were presented for each of the six experimental conditions. The 600 trials for any given experimental condition were run as four separate sessions, each consisting of 150 trials. Within any given session, the observers judged each of the six test elasticities 25 times.

Results and Discussion

In analyzing the results, cumulative normals were fit to the observers' data to create psychometric functions. Probit analysis was then used to obtain difference thresholds (i.e., Weber fractions). The difference thresholds were analyzed using a 2 (Elasticity) x 3 (Orientation) within-subjects analysis of variance to evaluate possible differences between the two standard elasticities and the three bending plane orientations.

Figure 2 shows the average difference thresholds for all observers. There was a significant main effect of the standard elasticity, such that the bending discrimination thresholds were significantly lower for the less elastic standard ($F(1,4) = 12.02$, $p = .026$, $\eta^2 = .75$).

The main effect of bending plane orientation was also significant ($F(2, 8) = 5.04$, $p = .038$, $\eta^2 = .56$). The observers' discrimination thresholds were highest when the rods bent within the fronto-parallel plane and were lowest when the rods bent within a plane that was oriented 42.5 degrees from fronto-parallel. In real world situations, bendings do not frequently occur completely in depth or completely in fronto-parallel orientations. Most bendings have both frontal and in-depth components (like our 42.5 degree condition). It is perhaps not surprising, therefore, that the observers' performance was best in that condition.

The average difference threshold for judgments of elasticity across all participants and conditions was 6.8 percent of the standard. This performance was good compared to that obtained for other 3-D tasks (Norman & Todd, 1996, 1998; Norman, Todd, Norman, Clayton, & McBride, 2006). This confirms and extends previous psychophysical research, which concluded that human observers are sensitive to bending (Jansson, 1977; Jansson & Johansson, 1973; Jansson & Runeson, 1977).

Chapter 3

Experiment 2

It is possible that the observers in Experiment 1 used 2-D properties of the projected motions (such as the magnitude of projected speed) in order to judge which 3-D rod within a trial was more flexible. After all, the tip of a more flexible rod will move faster than the tip of a less elastic rod when the same force is applied to both. The purpose of Experiment 2 was to measure the observers' difference thresholds for 2-D speed for conditions with the same average speed as those employed in Experiment 1. If the observers in Experiment 1 based their judgments of elasticity upon differences in projected speed, the obtained difference thresholds from Experiments 1 and 2 should be positively correlated (i.e., when observers perform well at judging speed differences, they should also perform well for discriminations of elasticity; conversely, when the observers cannot discriminate speed differences, they should be unable to discriminate elasticity).

Method

Observers

Observers JFN, HFN, EYW, and MJT from Experiment 1 also participated in Experiment 2.

Apparatus

The observers viewed the displays using the same apparatus that was used in the previous experiment.

Stimulus Displays

The stimulus display was a horizontally oriented rod composed of fifty white points (each was two pixels wide) presented against a black background. Each point was separated by 0.2 cm. In this experiment the rods did not bend, but translated in a vertical direction in the frontoparallel plane. The rods moved heterodimensionally (i.e., they translated from different starting points and for different durations within each trial). Each of the two temporal intervals within a trial had a random duration between 1.0 and 2.0 seconds. The presentation of the two translating rods was separated by a one-second inter-stimulus interval.

Procedure

The same procedures used for the bending rods in Experiment 1 were used when the observers judged the speed of translating rods in the current experiment (that is, there were 600 trials for each of the six standard speeds). On any given trial, the observers viewed two rods (one rod translated at a standard speed while the other translated at one of six possible test speeds) consecutively and reported which of the two appeared to be moving faster. The six standard speeds equaled the mean speeds of the projected motions produced in the six experimental conditions of Experiment 1. The six standard speeds used in the current experiment were 0.63, 1.56, 1.90, 2.05, 3.17, and 3.80 degrees (visual angle) per second. For each standard speed, there were six test speeds. The test rods moved 5, 15, or 25 percent faster than the standard rods or 5, 15, or 25 percent slower than the standard rods.

Results and Discussion

The results are shown in Figure 3. Once again, cumulative normals were fit to the observers' data to produce psychometric functions. Probit analysis was then used to calculate difference thresholds for each of the six standard speeds. The observers' best performance (lowest thresholds) occurred for the fastest standard speed (difference threshold of 10.6 percent for the 3.8 deg/sec standard speed), while their worst performance (highest thresholds) occurred for the slowest standard speed (difference threshold of 18.3 percent for the 0.6 deg/sec standard speed). The observers' difference thresholds were analyzed using a one-way within-subjects analysis of variance. The effect of standard speed was significant ($F(5,15) = 12.7$, $p < .0001$, $\eta^2 = .81$). The observers' thresholds (average of 13.0% across all standard speeds) were higher than those of McKee (1981), but were less than those of Mandriota, Mintz, and Notterman (1962) and Notterman and Page (1957). The current observers' speed discrimination thresholds were comparable to those of Hick (1950) and Snowden and Kavanagh (2006, see their Figure 4).

It is important to remember that if the ability to judge 2-D speed is responsible for the observers' ability to discriminate elasticity, then the results for the two tasks should be positively correlated. We found no such positive correlations. In fact, for HFN ($r = -0.42$), EYW ($r = -0.7$), and MJT ($r = -0.64$) we found negative correlations. JFN ($r = -0.09$) had a correlation of nearly zero. It would appear that improved abilities to judge differences in speed do not lead to improved abilities to discriminate differences in the elasticity of bending objects.

Chapter 4

General Discussion

The goal of Experiment 1 was to evaluate the perceptual sensitivity of human observers to the differences in elasticity of bending objects. This research fills a gap that currently exists in the psychophysical literature concerning the perception of nonrigid motion. If the human visual system contains mechanisms that are sensitive to bending, then elasticity discrimination performance should be good (that is, very good performance would be indicated by Weber fractions that are five percent of the standard or less; see Woodworth & Schlosberg, 1954, p. 195). If the human visual system is not sensitive to elasticity per se, then our observers would have to rely on secondary optical properties, such as speed differences, to make their judgments. This would have led to reduced levels of performance (i.e., higher Weber fractions).

The average threshold of 6.9 percent that was obtained in Experiment 1 shows that human observers have a good ability to discriminate bending, when that performance is compared to other visual tasks. The Weber fractions obtained for discriminations of binocular disparity range from 5.5 to 20 percent (McKee, Levi, & Bowne, 1990). The Weber fractions obtained for the discrimination of line length range from 3.3 percent to 26.3 percent (Norman, Todd, Perotti, & Tittle, 1996). The discrimination of surface curvature produces Weber fractions that are as high as 79 percent (Norman, Todd, Norman, Clayton, & McBride, 2006).

The results of Experiment 1 showed that human observers can precisely discriminate between bending rods that possess different elasticities. A comparison of Experiments 1 and 2 revealed that the observers' ability to discriminate elasticity was not based on their ability to discriminate differences in projected speed. The results of Experiment 1 also indicated that human observers could discriminate bendings in depth with about the same level of precision as they could discriminate bendings in the frontoparallel plane.

Because the observers performed well in the elasticity discrimination task and the performances obtained for the speed and elasticity discrimination tasks were not positively correlated, it is reasonable to conclude that the visual mechanisms involved in speed discrimination are not the same as those concerned with the perception of elasticity. Koenderink and van Doorn (1986) have developed a computational model that can successfully detect the 3-D structure of bending objects. It is possible that something resembling their model is functionally implemented within the visual cortex: the operation of this putative mechanism could be responsible for our observers' good performance for judgments of elasticity. It is also possible, however, that our observers based their judgments of elasticity upon static differences in curvature. All other things being equal (driving forces, etc.), objects that possess higher elasticities bend more, while objects with lower elasticities bend less. Perhaps the observers were comparing the curvatures of the bending rods while they were maximally bent. Future research is needed to determine whether visual mechanisms exist that detect elasticity per se, as opposed to differences in static curvature.

A better understanding of how human observers perceive nonrigid motion could facilitate efforts to develop autonomous robots that could successfully cope with the nonrigid motions present in the natural environment. Woodfill and Zabih (1991) have developed and implemented an algorithm that can track nonrigid moving objects. Polana and Nelson (1995) implemented an algorithm that can successfully recognize biological motion (both human and animal biological motion). Despite these developments, however, no algorithm currently exists that can interpret nonrigid motion as successfully as a human observer. The results of Experiment 1 show that human observers can easily perceive nonrigid motions in 3-dimensional space. Continued psychophysical research on the human perception of bending and other forms of nonrigid motion will ultimately help artificial intelligence researchers to produce mobile robots that can successfully navigate and operate within natural environments.

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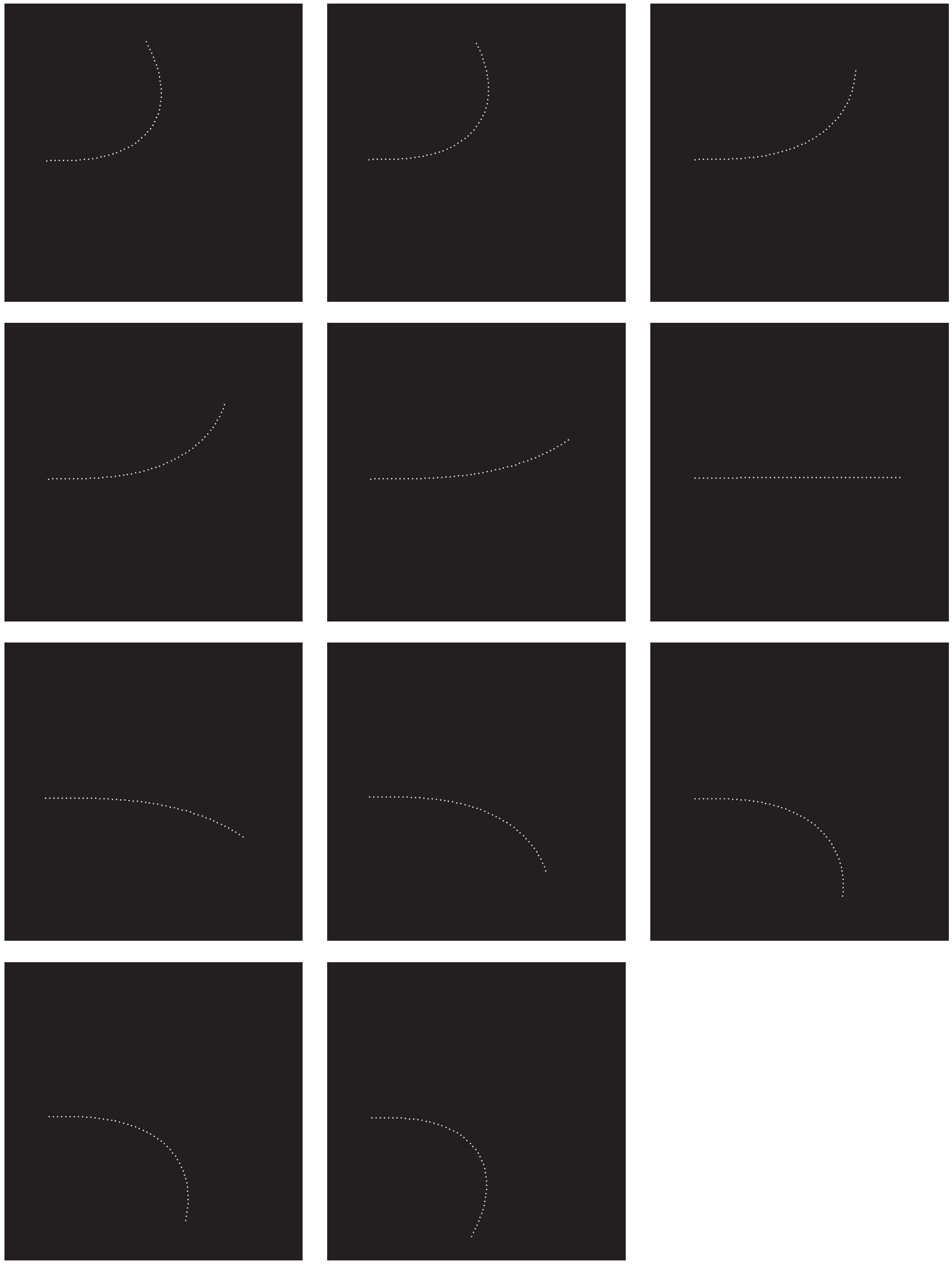

Figure 1. Eleven frames of an apparent motion sequence for the .02 elasticity standard. Frame 1 (upper left) represents the most extreme upward deflection and frame 11 (bottom right) represents the most extreme downward deflection.

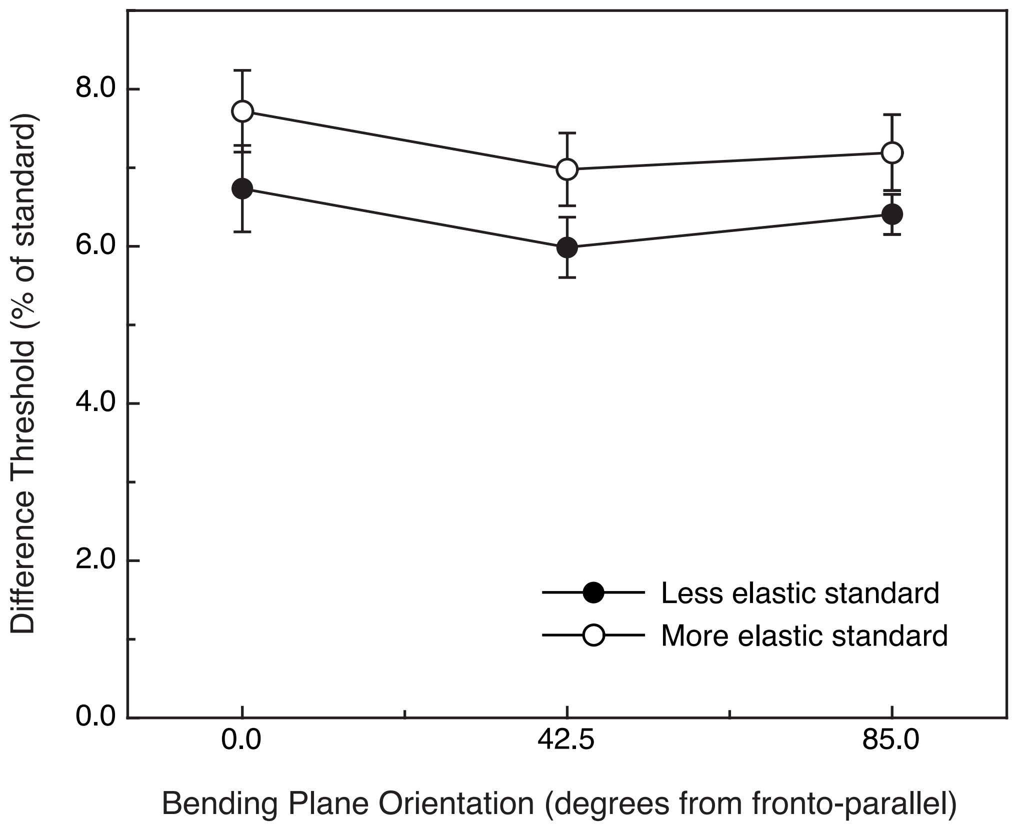

Figure 2. Average elasticity difference thresholds for observers JFN, HFN, EYW, SER, and MJT.

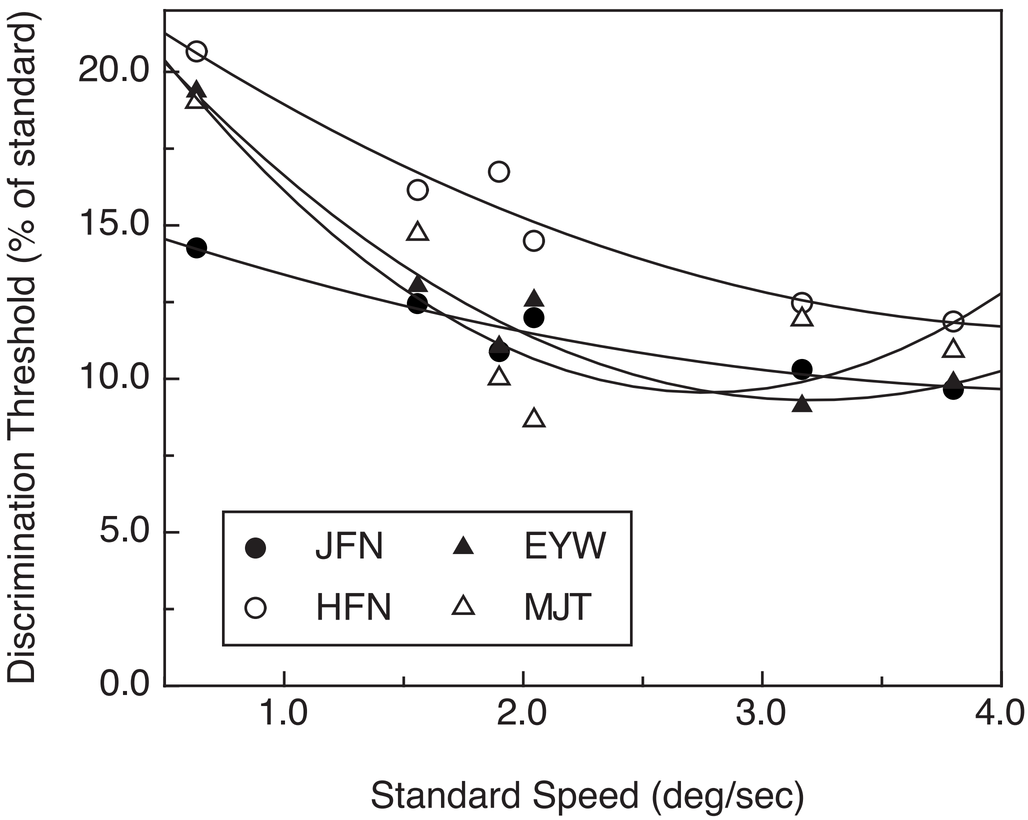

Figure 3. Speed discrimination thresholds for observers JFN, HFN, EYW, and MJT.