Journal of Experimental Psychology:
Human Perception and Performance
1995, Vol. 21, No. 6, 1473–1493

0096-1523/95/$3.00

Dynamics and the Orientation of Kinematic Forms in Visual Event Recognition

Geoffrey P. Bingham
Indiana University

Richard C. Schmidt
Tulane University

Lawrence D. Rosenblum
University of California at Riverside

The authors investigated event dynamics as a determinant of the perceptual significance of forms of motion. Patch-light displays were recorded for 9 simple events selected to represent rigid-body dynamics, biodynamics, hydrodynamics, and aerodynamics. Observers described events in a free-response task or by circling properties in a list. Cluster analyses performed on descriptor frequencies reflected the dynamics. Observers discriminated hydro- versus aerodynamic events and animate versus inanimate events. The latter result was confirmed by using a forced-choice task. Dynamical models of the events led us to consider energy flows as a determinant of kinematic properties that allowed animacy to be distinguished. Orientation was manipulated in 3 viewing conditions. Descriptions varied with absolute display orientation rather than the relative orientation of display and observer.

Forms of motion have been shown to provide information that enables observers to identify events (e.g., Cutting, Proffitt, & Kozlowski, 1978; Jansson, 1977; Jansson & Johansson, 1973; Johansson, 1973, 1976; Michotte, 1963; Todd, 1983). (See Bingham, 1995, for a review.) What in\ such motions with their specific significance? As suggested by Runeson (1977), part of the answer must lie in an investigation of the physical properties that determine the forms of events. For instance, animators have found that they must use dynamical models to generate convincing animations of events (Barzel & Barr, 1988; Green, 1989; Hahn, 1988; Isaacs & Cohen, 1987; Moore & Wilhelms, 1988; Platt & Barr, 1988; Wilhelms, 1987; Witkin, Fleischer, & Barr, 1987; Witkin & Kass, 1988). The challenge in their efforts has been in accommodating different types of events that require different forms of mechanics (Miller, 1988; Platt & Barr, 1988; Terzopoulos & Fleischer, 1988). Different types of events may require use of, for instance, rigid-body dynamics, hydrodynamics, aerodynamics, or biodynamics.

A question that arises naturally in the context of these observations is whether a taxonomy of events recognizable through their motions might relate to the varieties of dynamics distinguished in mechanics. This question is relevant to studies on structure from motion because many have used a rigid-motion assumption[1] (Hildreth & Hollerbach, 1987; Hildreth & Koch, 1987; Horn, 1986; Nalwa, 1993; Ullman, 1979, 1984, 1988). The problem is that nonrigid motions (i.e., all motions that are not rigid motions) have been treated in these studies as if they were arbitrary (e.g., see Hildreth & Hollerbach, 1987). They are not. There are specific varieties of nonrigid motions, including those of fluids or air, those of elastic or plastic substances, and animate motions (e.g., those of snakes or human limbs). In the context of event recognition as opposed to object recognition, rigid motion is but one of a variety of types of motion. The issue becomes not whether rigid motion is assumed in preference to a nonspecific and arbitrary alternative but whether rigid motion can be recognized along with a wide variety of dynamically distinct types of events. For instance, bending motions have been shown to be recognizable (Jansson, 1977; Jansson & Johansson, 1973; Jansson & Runeson, 1977), as have bipedial gaits (Johansson, 1973; Todd, 1983). But can hydrodynamic events be recognized and distinguished from aerodynamic events (as well as rigid-body events)?

We used the patch-light video technique developed by Johansson (1973, 1976) to isolate forms of motion as information about events. We selected events to represent different types of dynamics. The first type was rigid-body dynamics, which includes translatory and rotational motions

Geoffrey P. Bingham, Department of Psychology, Indiana University; Lawrence D. Rosenblum, Department of Psychology, University of California at Riverside; Richard C. Schmidt, Department of Psychology, Tulane University. Richard C. Schmidt is now at the Department of Psychology, Holy Cross College.

This research was supported by National Institutes of Health Grant AM-07412, National Science Foundation Grant BNS-902[illegible], and National Science Foundation Grant DBS-921[illegible]. Some of the research reported herein appeared previously in a working paper (Bingham, 1987a).

Correspondence concerning this article should be addressed to Geoffrey P. Bingham, Department of Psychology, Indiana University, Bloomington, Indiana 47405. Electronic mail may be sent via Internet to gbingham@indiana.edu.

[1] See Braunstein (1988) for a review of investigations of the rigidity assumption and the accompanying controversy. The assumption has been used in computational analyses of local flow. Todd (1984) has shown, however, that local rigidity is not required for successful perception of surface shape.

of (more or less) rigid objects impelled by gravity, elastic forces, constraint surfaces, and frictional forces. The elastic forces included those encountered during collisions. The frictional forces included air resistance, dissipation in imperfectly elastic collisions, and friction at points of contact between surfaces. We captured these properties in four events: a falling and bouncing spring, a pendulum, a ball rolling downhill, and a ball rolling after being struck.

For nonrigid motions, we selected among events involving hydrodynamics or aerodynamics. Fluid flows are typically constrained by rigid-body surfaces and often are perturbed by rigid-body motions. One example is the damped circular swirling flows exhibited by fluid in a container stirred with a rigid rod. Another is the splash followed by damped oscillating waves produced when fluid in a container is hit by a projectile. We chose these two events to capture motions peculiar to fluid flows. A familiar instance of nonrigid motion involving aerodynamics is that of wind-blown leaves in autumn. We used irregular tickets of paper blown from a surface so as to fall through the air to land on a second lower surface.

These events were all inanimate. We also wished to test displays that involved animate motions. Animate motions, generated by forces associated with musculature, can be described by biodynamics (Hatze, 1981; McMahon, 1984). Johansson (1973) demonstrated that observers were readily able to recognize human activity in patch-light displays that captured the full layout of the link segments. Johansson ([illegible]) showed, however, that more than the mere link-segment structure was involved because observers also were able to distinguish patch-light people from patch-light link-segment puppets. We wished to contrast trajectories generated by biodynamical forces with those determined by orientation-specific (central field) or position-dependent forces (i.e., gravity and elastics, respectively).

This specific contrast was motivated by current understanding of the dynamics of human motor control. Human limb movements have been modeled successfully in terms of collections of upright and inverted pendulums, and/or mass-springs depending on the type of activity (Feldman, 1980, 1986; Hogan, Bizzi, Mussa-Ivaldi, & Flash, 1987; McMahon, 1984). To the extent that the dynamics of simple inanimate devices and of human limb motions are similar, the two types of events should be confusable. On the other hand, a distinguishing property of human motions is that muscles provide a source of energy that can replace energy dissipated in the course of simple inanimate events. The pendular motions of human limbs exhibit a noisy limit cycle stability rather than simply running down, as would a free inanimate pendulum (e.g., Kay, Kelso, Saltzman, & Schöner, 1987). Also, the mass-springs used to model upper-limb motions are adjustable in terms of the location of the equilibrium point, the stiffness, and the orientation of the spring (Feldman, Adamovich, Ostry, & Flanagan, 1990; Hogan et al., 1987). Simple inanimate events and similar events involving human limb motions might be distinguished just to the extent that the dynamics of the two types of events are distinct and are revealed as such.

We selected two animate events to contrast with two of the rigid-body events described earlier. In each case, a performer attempted to reproduce the motions generated in the respective inanimate event. Both the compression spring and the pivoted rod were moved by hand along the same path to the same endpoints and at the same frequency as the corresponding inanimate events. These cases were expected to be maximally difficult to discriminate, especially the latter, because of the widely recognized similarity between human limb movements and pendulums (McMahon, 1984; Mochon & McMahon, 1980, 1981). In each case, only differences in the form of a trajectory along a common path would allow discrimination, placing the focus on trajectory form as visual information.

Patch-light displays isolate motions as information about events. When presented in freeze frame as static images, such displays are typically unrecognizable as anything but a random distribution of oddly shaped patches. When patch-light displays are presented in motion, movements in three-dimensional (3D) space can be perceived, and certain events can be recognized. Necessarily, the patches in patch-light displays correspond to significant amounts of surface area on actual embodied surfaces.[2] Also, the patches themselves are typically rigid, although the relation among the patches may or may not be rigid. Thus, although the contours of the patches are of arbitrary shape, those contours deform in displays in ways determined by perspective transformations that are relatively well understood to specify rigid 3D motions. Undoubtedly, observers should perceive motions of surface patches in 3D by virtue of the transformations occurring in patch-light displays. The question is, can observers recognize various events and properties of events given particular types of motions in 3D? If so, might their descriptions reflect the underlying dynamical character of the events, including grouping in terms of rigid-body dynamics, hydrodynamics, aerodynamics, and biodynamics?

As a second means of revealing the potentially important role of dynamics in event recognition, we manipulated the orientation of recorded forms of motion with respect to gravity. Due to the ubiquitous and directionally specific role of gravity in terrestrial events, the forms of events are asymmetric. Given such asymmetries, might the significance of a kinematic form depend on its orientation? Orientation with respect to gravity has been found to have some effect on the recognition of objects (Rock, 1973). Sumi (1984) has found that inverted patch-light displays of a person walking are often not recognized as such, although the motions may still be recognized as animate (see also Bertenthal, Proffitt, & Cutting, 1984). We varied the viewing conditions for our nine events to include observation of both upright and inverted displays. To control for relative orientation between observer and display, as opposed to the absolute orientation of displays with respect to gravity, we included upright displays viewed by inverted observers. If

[2] The majority of computer-generated displays have contained dots that fail to transform as they should, despite having noticeable spatial extent (as they must). Such displays provide, therefore, contractory information about the events being simulated. Patch-light displays do not introduce this confound.

orientation with respect to gravity determined judged-event identities rather than orientation with respect to the obse , then this would support the role of dynamics in determining the significance of kinematic forms.

The experimental task was to identify events observed in patch-light displays. Observers were asked to describe the kind of event, the objects involved, the nature of the motions, and the factors causing the motions shown in the displays. A free-response task was used together with two replications in which observers had to select properties from a list of descriptors. The latter, more constrained task facilitated objective scoring of the results, whereas the former free-response task guaranteed that the latter results were representative of unconstrained recognition.

Of course, we did not expect that the descriptions should read as if taken from a textbook on dynamics. Such expectations would fly in the face of both the long history of the development of mechanics (e.g., Dijksterhuis, 1961; Jammer, 1957) and abundant results showing that college students fail to describe the mechanics (i.e., either dynamics or kinematics) of events correctly (Caramazza, McCloskey, & Green, 1981; Clement, 1982; Gentner & Stevens, 1983; Runeson, 1974). Indeed, the relation between perceptible properties and language is an interesting and deep problem that remains unsolved. Our interest, however, was in the nature of perceptible properties, and we wished to avoid confounding this problem with the problem of description. Th we deemphasized the semantics of the descriptors themselves and assumed instead that whatever the nature of the relation between perceptible properties and descriptions, change or perturbation of the properties perceptible within a display should be reflected in changes in the pattern of descriptors used to describe the display. Our expectation was that the relative similarities and differences of the descriptors and their frequencies would reflect the relative similarities and differences in the underlying dynamics.

Experiment 1: Identifying Events

Method

Display Generation

Patch-light displays were recorded for nine events, using a ¾-in. Sony U-matic VCR, a videocamera, and a 19-in monitor. The experimenter, who manipulated objects in the events, wore dark clothing, including dark gloves and a hooded shirt. The background, including all wall, floor, and table-top surfaces, was covered with black cloth, rendering the experimenter and background surfaces invisible in all displays. When the displays were viewed, the monitor's brightness was turned down and contrast turned up, creating high contrast between patches and background so that onl ght patches appeared in all displays.

E 1 (free fall). A stiff black compression spring (30 cm in length, 1.5 cm in diameter) was slid over a black wooden dowel (1.2 m in length, 1 cm in diameter) inserted through the center of the spring coils. The dowel was held vertically and rested on a wooden table top. A single patch (7.6 cm wide) of white retroreflective tape was wrapped around the top of the compression spring. Only this patch was visible in the display. The spring was held near the top of the dowel, released, and allowed to free fall 1 m along the dowel and to bounce. The amplitude of the rising spring was .6 m. A single cycle from peak to peak was recorded in each display. Three instances of the event were recorded in sequence. Mean event duration was 1.22 s (*SD* = .12 s).

Event 2 (hand-moved spring). The same spring was moved by hand along the vertical dowel to the same endpoints as in Event 1. Using a metronome tuned to the frequency of the free fall and bounce, the experimenter practiced moving the spring to the endpoints at the same frequency as in Event 1 until he could do it accurately. Otherwise, the displays were identical to those of Event 1. Mean event duration was 1.27 s (*SD* = .07 s).

Event 3 (pendulum). A black wooden dowel (50 cm in length and 1.5 cm in diameter) was suspended from a peg, using a metal ring screwed into one end. A patch (7.6 cm wide) of white retroreflective tape was wrapped around each end of the dowel. The display began with the lower end of the dowel held up. The dowel was released and allowed to swing freely through 75° of arc. Two cycles were recorded in each of three instances. Mean event duration was 2.30 s (*SD* = .02 s).

Event 4 (hand-moved pendulum). The same dowel was moved by hand along the same path, at the same frequency, using a metronome tuned to the frequency of the freely swinging pendulum. The endpoints of the free pendulum trajectory were marked with tape on the monitor screen. Even with extensive practice, moving the dowel to successive endpoints corresponding to the decreasing amplitude of the damped free pendulum, while also reproducing the original frequency, was difficult. The experimenter reproduced the frequencies fairly accurately and the endpoints somewhat less accurately. Otherwise the displays were identical to those of Event 3. Mean event duration was 2.11 s (*SD* = .07 s).

Event 5 (rolling ball). A black lacrosse ball (7.5 cm in diameter) was allowed to roll down an inclined straight track (.75 m in length) from a static start. The track was elevated 15° from the horizontal. The ball was covered randomly with small irregular patches of retroreflective tape. The event was filmed from the side, with the camera tilted so that the ball rolled horizontally across the display screen. The ball rolled past the left edge of the display. Three instances of the event were recorded. The mean event duration was 3.11 s (*SD* = .17 s).

Event 6 (struck ball). The same ball as in Event 5 was nudged along a horizontal track by hitting the ball gently with a black dowel. The ball was hit three times, rolling to a stop the first two times and rolling off screen the third time. Three instances of the event were recorded. The mean display duration was 11.57 s (*SD* = .99 s).

Event 7 (stirred water). Irregular tickets of white paper (approximately 1.5 cm in average diameter) were randomly distributed so as to float on the surface of water in a large dark bowl. This was filmed from an angle above so that the liquid surface filled the entire display. The water was stirred around the edge of the bowl, using a black dowel. Only the white tickets appeared as irregular patches in the display. One instance of the event was recorded, and its duration was 9.05 s.

Event 8 (splash). Small clay balls (2 cm in diameter) were dropped into the center of the surface of the bowl of water used in Event 7. Three balls were dropped in sequence from a height of about 20 cm. The water was allowed to settle somewhat between impacts. Only the irregular patches were visible in the display. A single sequence was recorded, and its display duration was 11.08 s.

Event 9 (falling leaves). Irregular tickets of white paper (approximately 1.5 cm in average diameter) were blown off of a surface, located near the top of the display just beyond the right edge, so as to fall 1 m through the air to the surface of a table located near the bottom of the display. The tickets were then blown off the lower surface so as to travel past the left edge of the display. Only the irregular tickets appearing as bright patches could be seen in the display. One instance of the event was recorded. The display duration was 19.72 s.

The taped events were recorded, in order, onto a master presentation tape. To determine whether static images from these displays might be sufficient to specify the depicted events, images from Events 1, 3, 5, 8, and 9 were sampled using a frame grabber. The polarity of the images was reversed for cleaner printing. Informal studies revealed that none of these events was identifiable from static images, with the exception of Event 9, which could be guessed occasionally. In the latter instance, observers also suggested that the event could be many other things, including spots on a wall and floor or leaves on and under a tree. Sample images appear in Figure 1. One can see that such images are not very informative.

Procedure

All observers were situated approximately 4 m in front of the display screen, 2 to 6 observers in a session. The experimenter explained that a variety of simple events had been filmed so that only bright patches could be seen in the display.

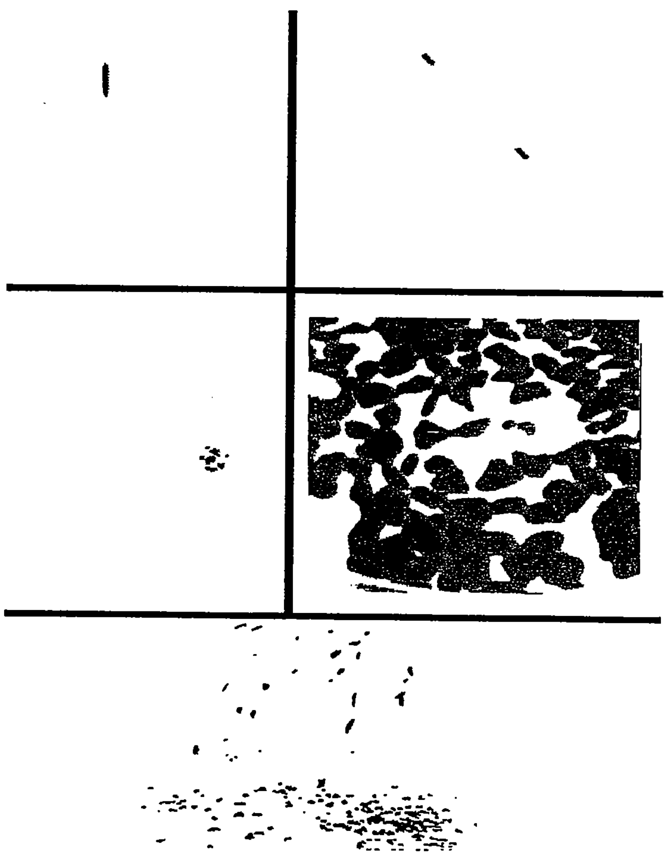

Figure 1. Static images from event displays: Event 1—free fall and bouncing spring (top right); Event 3—freely swinging damped pendulum (top left); Event 5—ball rolling downhill (middle right); Event 8—objects dropped in water (middle left); and Event 9—falling "leaves" (bottom).

Free-response task. Three different versions of the judgment task were run, in part, as replications. The first groups of observers participated in a free-response (FR) task. Observers were given a stapled packet of sheets of paper, 20 cm by 14 cm, one sheet for each of the nine events. The observers were asked to identify the events and to describe the motions, the objects involved, the causes of motion, and generally what was happening. They were told that if the event were recognizable, it would be relatively obvious. Also, they were told that they were not expected to be creative, to make up stories, or to interpret the displays as one might interpret a Rorschach inkblot. At the same time, observers were told that they should not adopt an analytical attitude and should not simply describe motions on the screen. Observers were told that if unable to recognize the event, they should simply say so, and that given the way the events were filmed (i.e., only spots moving on the screen), it was possible that they might not be able to recognize what was taking place.

Observers wrote their descriptions of the events in their own words on each subsequent sheet. Observers usually wrote 2 to 6 sentences to describe an event. The number of instances of each event that would be shown was announced before the displays were shown each time. The videotape was paused between events to allow observers to write their descriptions. Observers were instructed to watch all instances of each event before beginning to write, and they were allowed as much time to write as they desired. Observers were instructed to keep their attention oriented to either their writing or to the display and the experimenter, and not to regard the efforts of other participants.

CP48. A second version of the judgment task, circle properties—48 (CP48), was identical in procedure to the FR task except that observers were instructed to describe the events by circling relevant descriptors on a list. This second task was used to simplify the scoring of the results, whereas the original FR task was used to obtain unconstrained or strictly spontaneous descriptions of the events. Each of the nine sheets (21 cm × 28 cm) in the packet given to participants contained a list of 48 descriptors. The descriptors were listed in the order shown in Appendix A. Participants were allowed to scan the list on the topmost sheet before the displays for the first event were shown. The descriptors in the list included items derived from the results of the FR task as well as a few incorrect but reasonable foils. The list was kept to a relatively small number of descriptors so that participants would be well able to survey the list after each event in a fairly brief period of time. Subsequently, we observed that important descriptors were absent because of the brevity of the list (e.g., *water* and *pendulum* were not on the original list). A longer list would also allow the inclusion of more foils.

CP100. A third version of the judgment task, circle properties—100 (CP100), was run using a list of 100 descriptors ordered as shown in Appendix B. In other respects, the procedure was the same as before. We should stress that a proportion of the items appearing in the lists of the latter two circle-properties tasks were derived from the spontaneous descriptions of the observers in the original FR task. The latter tasks were used primarily to check the original pattern of results using a procedure allowing objective scoring. The emphasis throughout the tasks was on the pattern of responding. The duration of all experimental sessions was 50 to 60 min.

Viewing conditions. All three judgment tasks were performed in three different viewing conditions. In the first viewing condition (upright O and D), observers sat upright and observed upright displays. In the second viewing condition (inverted D), observers sat upright and observed inverted displays. Observers were given no information concerning the orientation of the displays. In the

FR and CP48 sessions at the University of Connecticut at Storrs, a Sony 19-in (48.3 cm) monitor was inverted. Nothing about the appearance of the monitor indicated its inverted position. The CP100 sessions took place at Trinity College in Hartford, CT, usi ʼn inverted Panasonic 24-in (61 cm) monitor. In the third vie. .g condition (inverted O), inverted observers viewed upright displays. Observers were inverted by having them lie on their backs on a table so that they could extend their head and neck beyond the edge of the table, allowing their heads to hang upside down while observing the display. To write their judgments, participants slid their heads back onto the table and sat up in a crossed-leg posture. Observers experienced no discomfort or any difficulty with blood rushing to their heads because most of the body was level and the inverted posture was maintained only for the few seconds required to observe the displays each time.

Participants

A total of 26 undergraduates at the University of Connecticut participated in the FR task for credit in an introductory course in psychology. Ten observers, 6 female and 4 male, were in the upright O and D condition. Eleven observers, 9 female and 2 male, were in the inverted D condition. Five observers, 4 female and 1 male, were in the inverted O condition.

A total of 33 undergraduates at the University of Connecticut participated in the CP48 task for credit in introductory psychology. Fourteen observers, 11 female and 3 male, were in the upright O and D condition. Twelve observers, 11 female and 1 male, were in the inverted D condition. Seven observers, 4 female and 3 male, were in the inverted O condition.

A total of 38 undergraduates at Trinity College participated in the 100 task for credit in introductory psychology. Fifteen observers, 8 female and 7 male, were in the upright O and D condition. Ten observers, 6 female and 4 male, were in the inverted D condition. Thirteen observers, 3 female and 10 male, were in the inverted O condition.

None of the observers reported having any motor or visual disabilities.

Results and Discussion

Generally, in all versions of the upright O and D condition, the events were recognized. For instance, in Event 1, the bouncing of an elastic object after free fall was recognized, although the compression spring was not usually recognized as such. Also, the constraint provided by the dowel was usually noted. The pendulum, stirred water, objects dropped into water, and "autumn leaves" were recognized as such. The ball rolling down an incline was distinguished from the struck ball. About half of the observers recognized the incline, whereas the remaining observers saw the ball as being pushed or blown by wind. The compression spring moved by hand was distinguished from the free-falling and bouncing spring, and frequently observers recognized that it was being moved specifically by hand. Observers had much greater difficulty distinguishing or re izing the pendulum moved by hand, although occasionally it was so recognized.

The results were first collated by tabulating the frequency of mention for each of the descriptors in the CP48 and CP100 lists. The FR protocols were scored by two independent scorers who used the CP100 list to categorize the responses. Frequencies of mention were then tallied as for CP48 and CP100 protocols. We expressed frequencies as percentages for ease of comparison.

To interpret the results, we did not rely primarily on the semantic of the descriptors used most often to describe each event. Rather, we examined the relative patterns of descriptors used across different events to see whether and how events were distinguished. We also examined possible changes in the relative pattern of descriptors used for each event across different viewing conditions. The results are shown in Tables 1 and 2. Table 1 lists FR and CP100 frequencies ordered for each event according to the frequencies in the FR upright display condition. Table 2 lists frequencies for CP48 ordered according to those for the upright display condition. For a property to be included in the tables, the sum of the frequencies across viewing conditions had to be greater than 20%. Properties that failed to meet this condition for FR but that were ≥50% for CP100 appear at the end of those lists.

In each list, properties that incorrectly described an event were marked with a footnote. In general, such marked properties appeared in the lower portion of the lists where frequencies were low. For each event and viewing condition, we counted the number of descriptors with frequencies ≥50% and then calculated the percentage of this number that were correct (i.e., without a footnote). Mean values across replications (FR, CP48, CP100) are shown in Table 3. Smaller percentages of correctly mentioned properties should indicate greater recognition difficulty, as should a smaller number of properties mentioned at least half of the time. However, percentages of correct properties were high (≥80%) in 20 of 27 instances, with 5.75 properties mentioned on average in those cases. The overall average number of properties mentioned correctly was 4.78, whereas only .63 were mentioned incorrectly (with frequencies of mention ≥50%). These results reflect a generally high level of recognition.

Nevertheless, some events and viewing conditions seemed to be more difficult than others. For instance, the inverted-display (ID) condition was often more difficult than either the inverted-observer (IO) or upright-display (UD) conditions. The overall mean percentages were 91.6% for UD, 80.7% for ID, and 86.8% for IO, whereas the mean number of properties mentioned at least 50% of the time were 6.1 for UD, 4.6 for ID, and 5.5 for IO. Some events were affected more by change in viewing condition than others. The stirred water, splash, and falling leaves events were relatively unaffected, whereas the free-swinging pendulum was most affected. Comparing by event type rather than orientation, the hand-moved spring and pendulum events were most difficult to recognize correctly, with mean percent correct across viewing conditions of 69% and 62%, respectively. Mean percent correct was above 90% for all other events except the free-swinging pendulum at 77%. The pendulum was most strongly affected by changes in orientation.

Next, we analyzed the patterning of descriptor frequencies for the different events by using cluster analysis. We

Table 1
Descriptor Frequencies for the Nine Events From the Free Response (FR) and Circle Properties 100 (CP100) Tasks

Property	UD FR	UD CP100	ID FR	ID CP100	IO FR	IO CP100
Event 1. Free fall and bounce						
Bounce	100	100	36	80	60	100
Free falling	100	67	18	30	60	69
Held/released	90	47	18	10	60	54
Dropped	90	93	9	20	60	92
Let go	90	53	18	20	60	46
Released	90	73	45	20	60	62
Spring	50	33	9	20	0	15
Ball[a]	50	7	18	30	40	8
Elastic	50	—	0	—	0	—
Flat surface	40	13	0	20	40	0
Stick	30	33	27	30	60	15
Rod	30	47	27	50	60	15
Human movement	30	—	27	—	80	—
Glass[a]	30	—	0	—	0	—
Hit	20	53	9	40	20	46
Machine[a]	0	—	18	—	20	—
Pulled[a]	0	—	45	—	0	—
Motor[a]	0	—	18	—	20	—
Pulled by string[a]	0	13	27	20	0	8
Rising	0	27	45	20	0	23
Straight path	—	93	—	80	—	85
Gravity	—	73	—	40	—	69
Event 2. Hand moved spring						
Human movement	60	7	27	20	100	0
Free falling[a]	60	33	9	20	20	46
Released[a]	50	60	27	50	20	54
Held/released[a]	50	73	18	50	20	38
Let go[a]	50	73	18	40	20	69
Dropped	50	73	18	10	20	77
Bounce[a]	50	60	27	60	40	92
Hand moved	40	27	27	20	40	28
Manual guidance	40	7	27	30	40	8
Rod	30	47	27	50	60	23
Ball[a]	30	0	9	20	40	15
Stick	30	40	27	30	60	8
Flat surface	20	—	0	—	40	—
Hit	20	67	9	30	0	69
Pushed	10	7	0	10	20	8
Slow	10	—	9	—	0	—
Perturbed	10	—	0	—	0	—
Landing	10	20	0	20	0	31
Machine[a]	10	—	18	—	20	—
Motor[a]	10	—	18	—	20	—
Spring[a]	10	—	18	—	0	—
Stopped	10	13	0	10	0	23
Thrown[a]	10	0	9	20	40	15
Air	0	—	0	—	20	—
Rising	0	40	36	20	0	31
Slowed down	0	13	0	10	20	8
Lifted	0	7	27	40	20	15
Straight path	—	73	—	60	—	62
Gravity	—	53	—	30	—	23
Impacted	—	27	—	20	—	69
Propelled	—	7	—	60	—	31
Event 3. Free-swinging pendulum						
Swinging	80	73	54	50	100	85
Held/released	70	73	0	20	20	62
Event 3. Free-swinging pendulum (*continued*)						
Pendulum	60	100	0	50	80	100
Released	60	73	0	30	0	54
Let go	60	67	0	10	20	69
Rod	30	40	27	20	20	23
Gravity	30	47	0	0	0	54
Stick	30	0	27	20	20	8
Dropped	30	20	0	0	0	23
Human movement	30	—	9	—	40	—
Machine[a]	10	7	36	60	20	15
Motor[a]	10	0	36	20	0	8
Wiper[a]	0	13	36	70	0	62
Metronome[a]	0	20	27	40	20	15
Inverted pendulum	—	7	—	50	—	54
Event 4. Hand-moved pendulum						
Swinging	70	80	73	40	100	62
Released[a]	50	47	0	50	20	54
Pendulum	50	100	9	50	60	100
Stick	50	—	18	—	20	—
Rod	50	33	18	10	20	8
Human movement	50	53	18	40	60	46
Rotating	30	7	9	10	20	15
Held/released[a]	30	—	0	—	20	—
Motor[a]	30	—	45	—	60	—
Machine[a]	30	0	45	30	60	0
Let go[a]	30	73	0	30	20	46
Hand moved	20	13	9	20	0	15
Manual guidance	20	20	9	20	0	8
Wiper[a]	0	13	45	80	20	69
Metronome[a]	0	33	27	30	20	15
Gravity	—	27	—	30	—	54
Inverted pendulum	—	7	—	60	—	31
Event 5. Ball rolling downhill						
Ball	100	87	91	90	100	85
Rolling	80	80	82	60	60	69
Speeded up	60	40	9	30	20	62
Straight path	40	87	9	60	0	69
Rolls downhill	40	0	0	20	20	38
Flat surface	30	67	0	0	20	38
Inclined surface	30	7	9	20	0	23
Slow	30	27	9	10	20	15
Air	30	—	0	—	40	—
Wind[a]	30	20	0	0	40	8
Hand moved	20	27	27	0	80	8
Pulled[a]	20	—	0	—	20	—
Pushed[a]	20	40	27	10	0	46
Manual guidance[a]	20	27	27	20	80	8
Human movement	10	—	27	—	80	—
Hit[a]	10	—	9	—	20	—
Kicked[a]	10	20	0	0	20	8
Blown[a]	0	27	0	0	40	15
Machine[a]	0	—	27	—	0	—
Motor[a]	0	0	27	20	0	8
Spinning	—	40	—	70	—	69
Rotating	—	40	—	60	—	77
Event 6. Struck ball						
Ball	100	100	82	90	100	100

Table 1 *(continued)*

Property	UD FR	UD CP100	ID FR	ID CP100	IO FR	IO CP100
Event 6. Struck ball *(continued)*						
Stopped	80	87	73	30	80	69
Rolling	60	80	64	50	20	92
Speeded up	50	60	18	40	0	92
Pushed	50	33	9	20	20	38
Human movement	50	—	54	—	20	—
Kicked	50	33	9	60	20	38
Straight path	20	60	9	50	0	77
Slow	20	33	9	30	0	23
Air	10	0	36	0	0	23
Machine[a]	10	—	18	—	0	—
Motor[a]	10	—	18	—	0	—
Wind[a]	10	—	36	—	0	—
Hit	0	33	18	0	20	31
Blown[a]	0	7	18	0	20	31
Slowed to stop	—	100	—	70	—	85
Flat surface	—	73	—	30	—	38
Manual guidance	—	53	—	10	—	23
Rotating	—	53	—	40	—	62
Spinning	—	33	—	40	—	54
Event 7. Stirred water						
Water	80	73	45	80	40	46
Floating	70	100	36	70	20	77
Leaves	60	33	45	30	20	23
Liquid	60	73	45	40	40	38
Vortex[a]	30	13	9	10	20	0
Whirlpool[a]	30	73	9	70	20	62
Swirling	30	67	18	80	20	92
Liquid surface	20	60	27	60	20	38
Rotating	20	73	64	70	60	92
Spinning	20	73	18	30	0	69
Slow	10	13	18	0	0	15
Machine[a]	10	—	9	—	40	—
Motor[a]	10	—	9	—	40	—
Air[a]	10	20	27	0	0	8
Human movement	10	—	18	—	20	—
Glass[a]	10	—	0	—	20	—
Stirred	10	67	18	50	0	62
Wind[a]	10	27	18	0	0	15
Blown[a]	0	20	27	10	0	15
Manual guidance[a]	0	—	18	—	20	—
Hand moved[a]	0	—	18	—	20	—
Flowing	—	27	—	50	—	23
Event 8. Splash						
Water	70	100	82	90	100	92
Liquid	70	100	82	60	100	92
Liquid surface	60	87	9	70	60	85
Floating	60	100	27	60	0	85
Dropped	60	80	54	60	60	70
Ripples	30	80	54	80	40	92
Perturbed	30	20	9	0	20	15
Leaves	30	13	36	40	40	38
Autumn leaves	20	7	9	40	0	31
Waves	20	67	36	60	20	62
Jello[a]	10	7	18	0	0	15
ks	10	27	18	50	20	38
Glass[a]	10	—	0	—	20	—
Thrown	10	53	18	60	0	23
Let go	0	33	54	0	0	31
Hit	0	27	0	20	40	38
Held/released	0	20	54	0	0	8
Free falling	0	27	9	0	20	38
Stirred[a]	0	27	27	0	0	15
Splashed	0	100	54	90	0	100
Released	0	27	54	0	0	31
Sinking	—	40	—	50	—	54
Gravity	—	40	—	0	—	54
Impacted	—	40	—	30	—	54
Event 9. Falling leaves						
Blown	100	87	91	90	80	92
Leaves	80	73	73	70	80	92
Air	60	73	100	50	80	62
Wind	60	80	100	70	80	92
Flat surface	50	33	18	30	40	23
Dropped	40	33	18	50	20	54
Autumn leaves	40	73	36	70	60	92
Free falling	30	47	18	40	40	31
Thrown[a]	30	13	18	10	20	31
Released	10	13	18	10	20	15
Let go	10	7	18	0	20	31
Human movement[a]	10	7	9	0	60	15
Machine[a]	0	—	27	—	20	—
Flowing	0	—	9	—	20	—
Upside down	0	0	36	70	0	23
Motor[a]	0	—	27	—	20	—
Floating	—	53	—	0	—	31
Landing	—	53	—	20	—	54
Gravity	—	40	—	50	—	54

Note. UD = upright display; ID = inverted display; IO = inverted observer.
[a] Incorrectly described an event.

performed cluster analyses on the frequencies clustered with respect to the nine events. A complete linkage method (farthest neighbor) was used with a Euclidian distance metric (Wilkinson, 1989). An analyses was performed on the combined frequencies from the three replications (FR, CP48, and CP100) in the upright O and D viewing condition. A tree diagram representing the relative distances between clusters corresponding to the nine events is shown in Figure 2. (The same results were obtained when the analysis was performed using data from the inverted O condition. Some change in the pattern resulted when the analysis was performed on inverted D data.)

There are three aspects of the pattern in Figure 2 that should be emphasized. First, the overall pattern would seem to reflect similarities and differences in the underlying dynamics. Working down the hierarchical tree from the right to the left in the figure, the six rigid-body events (1–6) were most closely related to one another, as were the two hydrodynamic events (7 and 8) and the aerodynamic event (9). This resulted despite the fact that Events 3–6, 7, and 9 all involved rotations, Events 1 and 9 both involved vertical movements, and Events 5–9 all involved complex motions of many patches. Thus, when the displays were upright, the underlying dynamics conditioned the grouping more than simple kinematic characteristics of the events.

Table 2
Descriptor Frequencies For Events 1–9 From CP48

Property	UD	ID	IO
Event 1. Free fall and bounce			
Bounce	100	33	100
Gravity	93	42	71
Drop	86	33	86
Fall	79	50	43
Straight path	79	92	100
Hand-started	64	58	29
Ball[a]	57	17	71
Flat surface	57	0	14
Hit	57	8	0
Spring	43	67	57
Rising	36	67	14
Flexible surface[a]	36	0	14
Elastic	29	50	29
Air	21	0	0
Machine[a]	14	8	0
Hand-stopped	14	42	14
Stretchy[a]	7	42	14
Hopping[a]	7	25	0
Pushed[a]	7	17	14
Pulled[a]	0	42	0
Launched[a]	0	67	0
Event 2. Hand-moved spring			
Drop	79	42	29
Straight path	71	42	71
Hand-started	64	67	29
Gravity	57	33	14
Hand-stopped	50	67	57
Flat surface	50	0	29
Hand-guided	43	50	86
Rising	43	75	14
Fall	43	42	29
Bounce[a]	43	50	43
Pulled	36	42	29
Ball[a]	29	33	14
Launched[a]	29	50	14
Elastic[a]	21	33	29
Magnetic[a]	21	17	0
Machine[a]	21	8	14
Hit	21	8	14
Spring[a]	21	50	29
Sticking[a]	7	8	29
Stretchy[a]	7	42	14
Flexible surface[a]	7	25	0
Molasses[a]	0	8	14
Pushed	0	50	0
Event 3. Free-swinging pendulum			
Swing	100	67	100
Gravity	50	8	29
Hand-started	50	33	29
Machine[a]	36	67	43
Metronome[a]	36	50	29
Windshield wiper[a]	36	50	71
Hand-stopped	14	42	14
Magnetic[a]	14	8	0
Moves all about[a]	14	8	0
Pushed[a]	14	8	43
Flow[a]	14	17	14
Flat surface[a]	7	25	0
Straight path[a]	7	0	14
Hand-guided[a]	7	25	0
Pulled[a]	0	8	14
Spring[a]	0	25	14
Event 4. Hand-moved pendulum			
Swing	100	83	71
Hand-started	86	25	57
Gravity	71	17	29
Hand-stopped	29	25	29
Windshield wiper[a]	29	33	57
Metronome[a]	21	58	57
Hand-guided	14	17	14
Pushed	14	17	0
Inclined surface[a]	14	8	0
Machine[a]	14	50	29
Drop[a]	14	0	14
Settling[a]	14	0	0
Flow[a]	14	8	0
Straight path[a]	7	0	14
Sticking[a]	7	0	14
Stretchy[a]	0	8	14
Elastic[a]	0	8	14
Bounce[a]	0	17	14
Spring[a]	0	50	14
Pulled	0	25	29
Event 5. Ball rolling downhill			
Ball	100	92	100
Flat surface[a]	64	50	71
Hand started	64	67	71
Pushed[a]	64	58	57
Straight path	57	58	86
Inclined surface	43	17	14
Gravity	43	8	43
Flow[a]	29	17	14
Wind[a]	21	17	0
Hand guided[a]	21	33	29
Blown[a]	14	33	0
Pulled[a]	14	8	0
Swirling[a]	7	33	14
Fall	0	8	14
Hand stopped[a]	0	33	0
Event 6. Struck ball			
Ball	100	83	100
Flat surface	71	33	86
Pushed	71	33	71
Straight path	57	58	57
Hand started	57	58	71
Hand guided[a]	36	58	29
Hit	36	25	71
Blown[a]	36	50	29
Settling	21	8	14
Launched	14	17	0
Air	14	25	0
Hand stopped[a]	14	25	29
Flow[a]	14	8	0
Gravity	14	8	0
Wind[a]	14	25	29
Sticking[a]	14	8	14
Swirling[a]	7	17	14
Pieces of paper[a]	7	17	0
Moves all about[a]	0	8	14
Event 7. Stirred water			
Swirling	86	92	86
Pieces of paper	79	75	86
Floating	79	83	86
Moves all about	79	83	57
Liquid	71	33	57

Table 2 *(continued)*

Property	UD	ID	IO
Event 7. Stirred water *(continued)*			
Stir	64	42	43
Flow	36	17	43
Wind[a]	36	58	57
Leaves[a]	36	25	14
Air[a]	29	42	14
Flexible surface	29	25	14
Blown[a]	21	42	43
Bumpy surface[a]	14	17	14
Cloth[a]	7	17	14
Splash[a]	7	0	14
Suction[a]	7	17	14
Event 8. Splash			
Liquid	93	92	86
Splash	93	58	86
Pieces of paper	86	67	71
Floating	86	92	57
Drop	57	42	86
Moves all about	50	8	14
Settling	43	33	14
Flexible surface	43	25	57
Sinking	36	17	14
Fall	36	0	29
Leaves[a]	29	17	14
Gravity	29	0	0
Hit	29	17	0
Flow[a]	21	17	14
Flat surface[a]	7	8	14
Stir[a]	7	17	0
Bounce	7	8	14
Event 9. Falling leaves			
Blown	100	92	71
Air	100	50	71
Wind	93	75	86
Pieces of paper	86	75	71
Leaves	71	67	71
Gravity	64	25	29
Fall	57	33	43
Flat surface	50	17	14
Drop	36	0	71
Moves all about	36	42	29
Launched	36	8	0
Settling	36	17	29
Floating	29	0	0
Hopping[a]	21	25	29
Swirling	21	17	14
Sticking[a]	14	25	14
Stir[a]	14	17	14
Sinking	7	0	14
Rising	7	42	14
Flow	7	0	14
Suction[a]	7	33	0
Magnetic[a]	0	42	0

Note. CP48 = Circle properties—48.
[a] Incorrectly described an event.

Second, although the rigid and nonrigid motions were in all cases clearly distinguished from one another at the most superordinate level, subordinate types of events were discriminated in each case. Different types of nonrigid events, involving motion through air as opposed to on water, were as strongly distinguished as were different types of rigid-body events involving linear free fall as opposed to rotational swinging or rolling motions. The results nevertheless did support a treatment of the rigid versus nonrigid distinction as fundamental in event recognition.

Third, when biodynamics were included in the context of two of the rigid-body events, the resulting animate events (2 and 4) were distinguishable from their inanimate counterparts (Events 1 and 3), if only weakly so. Focusing on the bottom of the tree at the left in Figure 2, each animate event was most closely paired with its inanimate counterpart, although the two in each instance were not equated. According to this analysis, Events 3 and 4 (pendulum) were the least well distinguished, whereas Events 1 and 2 (free fall and hand-moved spring) were as well distinguished as were Events 5 and 6 (rolling vs. struck ball) and almost as well as were Events 7 and 8 (stirred water and splash).

Next, we focused on the effect of viewing conditions. To capture the strength of the relations among conditions, we performed simple linear regressions, regressing the descriptor frequencies for a given event in one viewing condition on those for the same event in another viewing condition. If the events were judged similarly in two conditions, then descriptors with low frequencies in one were expected to correspond to low frequencies in the other and so on. Events that were judged differently were expected to yield low r^2, low slopes, or both. Before we performed each regression, we removed those descriptors with zero frequencies in both instances. (The pattern of results was the same when we retained these descriptors, but the r^2 and slopes were greater, whereas the intercepts were kept near 0.) Descriptor frequencies in the upright O and D condition were regressed alternatively on those in the inverted D or the inverted O conditions. Likewise, those for inverted O were regressed on those for the inverted D condition. The regressions were performed separately for each replication. The results were essentially the same. The mean r^2 and slopes are shown in Figure 3, with standard error bars to indicate the amount of variation between replications. (The results were also the same when we used the frequencies from the three replications together in combination.)

Comparable results were obtained when either upright O and D or inverted O were regressed on inverted D, as can be seen in Figure 3. With inversion of the display, there were changes in the descriptor frequencies so that these regression slopes and r^2 tended to be low. This effect was strongest for the first four events, but it was absent for the stirred-water display. The latter event involved no vertical motion and was filmed from a fairly high angle so that the gradient in the display projected from the patches on the surface of the water was slight. Thus, the display was nearly symmetric with respect to inversion. These results contrasted with the regressions of upright O and D on inverted O frequencies. In the latter case, the r^2s were consistently high, as were the slopes, indicating that the results were similar when the display was upright with little effect of change in the orientation of the observer.

We tested the significance of slope changes by combining the frequencies from all three replications and performing multiple regressions. First, we regressed upright O and D frequencies on those from inverted D and inverted O (com-

Table 3
Properties Named With a Frequency Greater Than or Equal to 50%: Percentage Correct and Number of Properties

	Viewing condition					
	UD		ID		IO	
Event	% Correct	Properties	% Correct	Properties	% Correct	Properties
1. Free fall and bounce	93	8.7	86	3.3	94	7.3
2. Hand-moved spring	60	7.0	62	4.7	86	4.3
3. Free-swinging pendulum	100	4.3	55	3.3	75	4.0
4. Hand-moved pendulum	78	4.3	50	3.0	57	4.7
5. Ball rolling downhill	93	4.0	93	4.0	87	5.3
6. Struck ball	100	7.3	87	5.0	100	5.7
7. Stirred water	100	6.3	93	4.7	94	4.3
8. Splash	100	6.7	100	7.7	94	7.0
9. Falling leaves	100	6.7	100	5.7	94	6.7

Note. UD = upright display; ID = inverted display; IO = inverted observers.

bined in a single vector) with a vector coded orthogonally for viewing condition and an interaction vector (Pedhazur, 1982). This tested the significance of difference between the leftmost and middle bars representing slopes in the lower panel of Figure 3. All nine multiple regressions were significant, $p < .001$, with r^2 between .38 and .66. Slope differences were significant, $p < .01$ or better, for Events 1–4, 6, and 8, whereas that for Event 5 was marginal, $p = .08$. (These regressions were performed after removing descriptors with common zero frequencies in each case. When the descriptors were retained, the overall r^2 ranged between .52 and .76, and significant slope differences were obtained in all cases except Event 7, stirred water.)

Next, we tested the differences between the leftmost and rightmost bars for each event shown in the lower panel of Figure 3. We regressed inverted D frequencies on those from upright O and D and inverted O (combined in a single vector) with a vector coded orthogonally for viewing condition and an interaction vector. All nine multiple regressions were significant, $p < .001$, with r^2 between .17 and .65. Slopes were not significantly different except for Event 4, $p < .05$. Event 4 results were affected more by inverting the display than the observer. We do not understand why the perception of this event in particular should be affected by inversion of the observer.

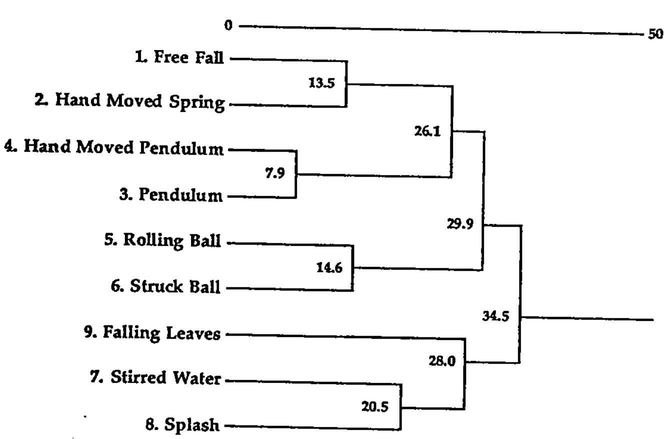

Figure 2. Tree diagram from cluster analysis of combined frequencies from the three replications. Frequencies for each of the descriptors were clustered into nine groups. Distances are listed at each node.

Overall, these analyses show that inverting the display produced results that were different from those obtained when the display was upright no matter what the orientation of the observer. The effect was strongest for the first four events and moderate for the remaining events except Event 7, stirred water, for which no effect was obtained.

All of these analyses were intended to place strong emphasis on changes in the patterns of descriptors as evidence for relative identification and change in perceived identity. We advocate caution in interpreting results in terms of the semantics of the descriptors themselves. Nevertheless, we will briefly review the FR descriptions for each event (including the effects of viewing condition). The FR results were generally reproduced by the CP results. We first compare animate and inanimate versions of the rigid-body events and then compare the rigid to the nonrigid events.

Rigid-Body Events

Event 1, free fall and bounce, was described in upright O and D and inverted O conditions as an object released, dropping and/or falling and bouncing, but in the inverted D condition it was described as a video game or a machine or as something thrown or pulled upward and then bouncing (i.e., the descriptions changed to machines, elastics, and other energy sources that could send an object upward). The straight path constrained by the dowel was noted in all cases.

Event 2, hand-moved spring, was usually distinguished from Event 1 but was recognized as human-limb motion only about half the time. Of those who did not recognize human movement, two observers described Event 2 as the same as Event 1, whereas others said it seemed slower, or that the path was strange, and one listed bounce in scare quotes, implying that it did not really look like a bounce.

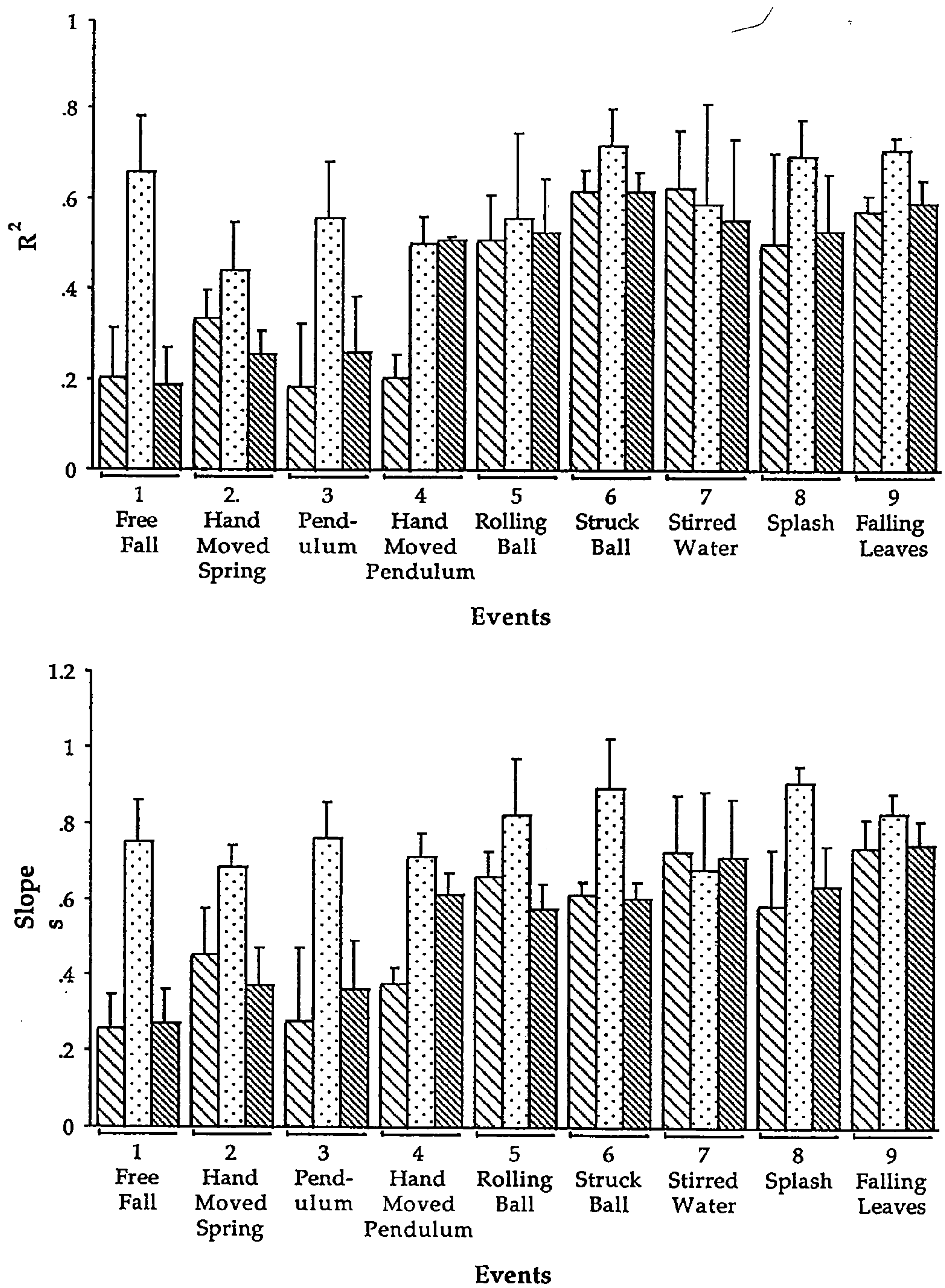

Figure 3. Bar charts representing results obtained for each type of event when descriptor frequencies from one viewing condition were regressed on those from another in each of the three replications. Means across the three replications are shown with standard error bars. Sparsely striped bars: Upright observer (O) and display (D) frequencies regressed on those for inverted D. Dotted bars: Upright O and D frequencies regressed on those for inverted O. Densely striped bars: inverted O frequencies regressed on those for inverted D.

Observers recognized the pendulums in both Events 3 and 4. Generally, Event 4, hand-moved pendulum, was not recognized as manually guided. However, two of the FR observers did describe Event 4 as moved by hand. For instance, in the upright O and D condition, one observer wrote a "person holds one [end] and mimics a swinging motion by moving the bottom with his hand." Thus, it appears that it might be possible to discriminate human limb motion in this case, although with extreme difficulty. We explored this in a subsequent experiment reported later.

In pilot experiments, observers had no difficulty recognizing a patch-light ball rolling down an incline. In the current experiment, we perturbed the viewing condition by filming the ball in Event 5 so that the incline did not appear in the display. Tilting the camera introduced some ambiguity. Although the rolling ball was well recognized, the downhill motion seems to have been recognized only by observers who focused on the motion as such, whereas those who especially noted the level path suggested that the ball was moved by hand or by wind.

The inverted display of Event 5 had a swirling, oddly confused appearance. Four of the observers described the ball as "rolling backward even though it moves forward." A fifth observer suggested that the film was being shown backward. Observers in the inverted O condition did not have these difficulties. Analysis of the kinematics of a rolling ball reveals an asymmetry of pattern specific to the gravitational direction (Bingham, 1995). A zero velocity is momentarily exhibited by points on the ball in contact with the surface along which the ball rolls, whereas the points on the opposite side of the ball move at twice the tangential velocity of the center of mass of the ball. For the ball to remain in contact with the constraint surface, the zero velocity point, and thus the constraint surface itself, must be at a level below center of mass of the ball. Inverting the display of Event 5 violated this condition. The display might have looked somewhat like an open umbrella being twirled backward as it moved forward, but given the lack of a constraint surface, an umbrella would not produce an invariant zero velocity point at its top. Perhaps for this reason the rolling ball was usually recognized despite the oddity of the inverted display.

Observers generally described Event 6 as a rolling ball being kicked by a person or occasionally being blown by gusts of wind. One observer in the upright O and D condition wrote "its not an incline; there is no gravity, so it has to be pushed; someone is pushing it."

Nonrigid Events

Each of the three nonrigid events was easily recognized in all viewing conditions. Event 7 was recognized, whether upright or inverted, as objects floating in water that was being stirred. In descriptions of Event 8, splashing and wave motion replaced the swirling of stirred water. Finally, Event 9 was recognized as a nonrigid event involving air rather than water, that is, as falling leaves. When the inverted orientation of the display was not recognized, the nature of the description changed from free fall to rising by virtue of magnetic attraction or a vacuum suction.

Altogether, the results indicate that the events could be recognized by virtue of the motions in the displays. Distinct rigid-body events were identified. Inanimate rigid-body events were often discriminated from similar rigid-body events involving animate activity, although limb motions were not easily distinguished from free, damped pendulum motions. Various types of nonrigid events were distinguished from rigid-body events that shared rotation of a collection of patches. Most important, distinct types of nonrigid events were identified, including different events involving water and events involving flow through air.

Finally, altering the orientation of event kinematics with respect to the gravitational direction often changed the perceived significance of the displays. Even subtle manipulations of orientation such as the tilting of the camera used to film the ball rolling downhill affected the perceived significance. Changing the relative orientation of the observers with respect to the displays did not tend to produce the same effect. The perceived significance of the displays only tended to change when the display's orientation to gravity changed. This suggests that event perception is multimodal[3] because observers can perceive the gravitational direction through the vestibular and somatosensory systems as well as by vision. These have been construed functionally as parts of a single system that Gibson called the *orienting system* (Gibson, 1966; Stoffregen & Riccio, 1988). The advantage of being oriented in the context of event identification is that gravity can relate perceivers to events with gravitationally produced kinematic asymmetries.

The change in perceived event identity with change in display orientation also indicates the importance of dynamical factors in event identification. Implicitly, what changed with a change in orientation was the role of gravity in determining the form of an event. With altered orientation, aspects of form originally generated by gravity must be perceived, if possible, in terms of other dynamical factors, elastics, springs, motors, and the like. This seemed to be possible for Event 1, in which inverted gravitational acceleration was often perceived as a stretched elastic pulling the object upward. The question is whether trajectories generated by gravity, as opposed to an elastic, are truly indistinguishable.

In other instances, events were recognized despite the alteration in orientation. The inverted rolling ball looked very strange and confusing, with the implication that the kinematics could not be confused with those of a different event with a different dynamic. We infer that the strong asymmetry of the kinematics was specific to gravity and was used to discern the orientation of the display and to reveal the ruse.

Experiment 2: Examining Trajectories' Forms as Visual Information

Next, we examined the trajectories of the animate and inanimate versions of the free-fall and pendulum events and performed an additional test of their discriminability. In the first studies, Events 1 and 2 (free fall and hand-guided spring) were usually distinguished despite commonality of path, amplitude, and frequency. In principle, only the form

[3] Cornilleau-Pérès and Droulez (1990) have suggested that the perception of "object-motion" requires only visual information and is thus fundamentally different from the perception of egomotion. The latter they describe as requiring multimodal information.

of the trajectories should have remained as a source of information allowing these events to be distinguished. The trajectories can be characterized in event space, that is, a plot of velocity versus position and time (for each of the sp coordinates). By projection, however, trajectories in subspaces of event space can be derived, including plots of position versus time (i.e., a time series), velocity versus time, or finally, velocity versus position. The latter, called *phase space,* is sufficient to characterize the differences between free falling and hand-moved trajectories of the spring because the events were synchronized in time.

We measured the kinematics of Events 1 and 2 by measuring the screen coordinates of the patch on the compression spring. The coordinates were measured in successive video frames that sampled the original event at 30 Hz. The mean (and *SD*) amplitudes in screen units were 67 (2.0) versus 65 (1.2) for Events 1 and 2, respectively. The times for descent were .768 s (.04) versus .715 s (.03). Given the 33 ms sampling interval, the 53 ms mean difference was negligible.

The position data were filtered using a Fourier-based method with a Gaussian window five samples in width. These data were then differentiated using central difference. The resulting phase space trajectories appear in Figure 4. Motion in the free fall and bounce event occurred only along the *Y* axis, so we plotted the trajectories in a Y–V_Y phase portrait. Trajectories for the three free-fall and bounce displays in the top panel of Figure 4 revealed the parabolic shape corresponding to gravitational acceleration with a flat ba: nerated by elastic impact and rebound. (The bottom of these trajectories were somewhat rounded due to the filtering.) Only about half of the original height was regained by the spring on the rebound due to dissipation of energy in the imperfectly elastic spring.[4]

The trajectories for the three hand-guided spring displays appear in the lower panel of Figure 4. These trajectories exhibit the elliptical form characteristic of human limb movements (Cooke, 1980). However, the peak velocities during the falling segment of the trajectories were displaced away from the midpoint of the fall, toward the bottom, and the early portions of the fall were more parabolic than elliptical. These two properties indicate that the hand was initially allowed to free fall before voluntary control was exerted.[5] Although the trajectories exhibited a short flat base corresponding to impact, the flat portion did not extend across the zero-velocity axis, indicating that the collision was inelastic.

One way of comparing forms is in terms of their symmetries. The free fall and bounce trajectories exhibited spatial symmetry. In contrast, the hand-guided trajectories were temporally symmetric. The symmetries were revealed through transformations that allowed portions of the trajectory to be made congruent. Because we were interested in form comparisons (rather than scale changes), we rescaled the :ond half of the free-fall trajectory to eliminate the effect of dissipation. After this, the two halves of the trajectory could be made congruent by folding the trajectory about the zero-velocity axis. That is, by taking the absolute value of velocity, the result would be matching velocities at corresponding positions. In contrast, to be made congruent, the halves of the hand-guided trajectory would not only have to be rescaled and folded about the zero-velocity axis, but the second half of the trajectory would have to be flipped left to right in the figure because the falling and rising motions were accelerated in similar ways. The necessity for this last flip reflects the temporal symmetry (and the spatial asymmetry) of the trajectory. The spatial symmetry of the free fall and bounce reflects the roles of gravity and elastic rebound in generating the form of the event. The spatial asymmetry of the hand-guided spring reflects the role of skeletal muscles and inelastic impact in generating the event. These differences in "rebound" are reflected in the relative location of the peak velocity. For the free fall, the peak occurred at the rebound. For the hand-guided movement, it did not.

We next examined the trajectories for Events 3 and 4, that is, the free-swinging and hand-guided pendulums. Noting that the occasional observer in the first studies did recognize human limb motion in Event 4, we wondered what the nature of these trajectories was that made them so difficult to distinguish, but left their discrimination a possibility. We had intended the free and hand-moved pendulum trajectories to be the same in path, amplitude, and frequency. However, we found that reproducing the regularly diminishing amplitude of the damped pendulum at the required frequency was difficult.

We measured the screen coordinates of the patches at the two ends of the rod. A line drawn between the two points rotated about a single image point over successive frames. We reduced the degrees of freedom of our measurements from *X* and *Y* coordinates to a single angular coordinate, θ. We differentiated the angular position data and filtered the resulting angular velocities using a Gaussian window of three samples in width. The resulting phase trajectories appear in Figure 5.

All three free-swinging, damped pendulum trajectories looked the same as that shown in the top panel of Figure 5, where the characteristic spiral can be seen. Amplitudes in successive half cycles decreased due to damping from friction at the pivot and air resistance. Two of the three hand-guided pendulum trajectories appear in the two lower panels of Figure 5. (The remaining trajectory was almost identical to that in the lower-right panel of Figure 5.) All failed to produce the continuous spiral on the phase plane, yielding instead crossing trajectories. Each trajectory crossed itself at least once, that shown in the lower left panel crossed itself

[4] This surmise was confirmed by modeling the event as projectile motion, alternatively with and without a viscous term representing air resistance, combined in a piecewise continuous fashion with a stiff damped mass-spring oscillator representing the impact portion of the trajectories. The best simulation was obtained with a version of the model without air resistance in which the energy of fall was dissipated in the mass spring.

[5] This was confirmed through simulations in which the falling trajectories were best modeled in a piecewise continuous fashion, including projectile motion for the initial portion and a harmonic oscillator for the latter portion.

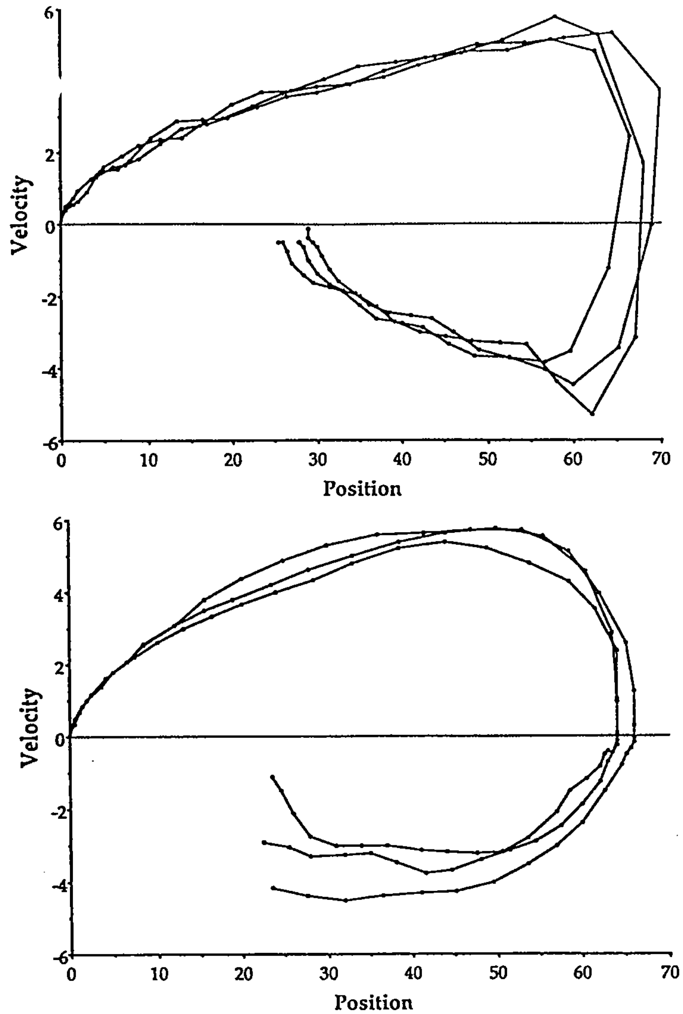

Figure 4. Top panel: phase space trajectories for three displays of the free falling and bouncing spring. Bottom panel: Phase space trajectories for three displays of the manually guided spring. (Arbitrary screen units)

twice. Information associated with this crossing of trajectories might allow the careful observer to distinguish the free and hand-moved pendulums. If observers were able to distinguish the two types of events, this should have been the only information available to do so, because the shapes of the trajectories were essentially the same otherwise.

Could observers truly distinguish free and hand-moved trajectories for either the free fall and bounce or pendulum events? To further test this possibility, we used the displays from the previous study in a forced-choice task.

Method

Procedure

The 12 displays from the original identification study were used: 3 free fall and bounce displays, 3 hand-guided spring displays, 3 free-swinging pendulum displays, and 3 hand-guided pendulum displays. These were presented to observers four times each, together in random orders blocked by trial. The observer's task was to judge in each instance whether the movement was natural, free movement, or whether the respective object was moved by hand through the entire event. The experimenter explained that the events had been filmed so that only one or two bright patches would appear in an otherwise dark display. An interval of a few seconds was provided to write judgments between displays. Observers performed the task in groups of four. Each observer performed 48 judgments. An experimental session took about 20 min.

Participants

Undergraduates at the University of Connecticut (N = 18) participated in the experiment for credit in an introductory psychology course. Eleven observers were male and 7 were female.

Results and Discussion

Observers were able to discriminate free motion from hand-guided motion in both types of events. However, they seem to have had more difficulty in recognizing the hand-guided pendulum.

The pattern of results is shown in Table 2 for both events. Chi-square tests performed on the data were significant in both cases, for the free fall and bounce, χ^2 (1, N = 432) = 193.7, $p < .01$, and for the pendulum, χ^2 (1, N = 432) = 21.9, $p < .01$. However, these data included repeated observations, so we performed separate chi-squares on the data for each of the four trials in each event, using a correction for continuity (Spence, Underwood, Duncan, & Cotton, 1968). The table for each trial exhibited the pattern shown in Table 4 for the respective type of event. The four chi-squares for the free fall and bounce were all significant, $p <$ .01, with $40.8 < \chi^2$ (1, N = 108) < 53.7. Three of the four chi-squares for the pendulum were significant, $p < .05$ or better, $4.8 < \chi^2 < 11.1$, whereas that for Trial 3 was not significant, χ^2 (1, N = 108) = .6. The results indicate that the animate motions could be discriminated in both cases but that observers had more difficulty in discriminating the hand-moved pendulum.

We examined the pendulum judgment data of each observer and found that approximately a quarter of the observers reliably discriminated both the free-swinging and the hand-guided pendulum in all displays, whereas the remaining observers were unreliable in their judgments of the hand-guided pendulum. (None of the hand-guided displays was more reliably identified than another.) We inferred that a few observers were skilled at discerning the hand-guided pendulums, whereas the others were not. All of the observers were able to distinguish the hand-guided spring. The results confirmed those of the earlier study showing that animate activity can be discriminated in these simple events but that manual guidance of a pendulum is more difficult to detect.

Dynamical Analysis of the Animate Events

We discovered different properties in two different types of events that might have enabled observers to distinguish animate from inanimate motions in each case. The rebound trajectory was different in the spring events, whereas in the pendulum events the trajectories either did or did not cross. The question was, why might these kinematic properties make the events look animate? Although the relevant properties in the two instances were different, we attempted to identify a single dynamical principle that might underlie the recognizably animate motions in each case. We modeled the respective event dynamics. From these dynamics we deduced potential dynamical criteria for animacy.

We first modeled the free fall and bounce. Because of the discontinuity associated with impact, a piecewise continuous model had to be used (Thompson & Stewart, 1986). The free-falling and rising portions of the event were modeled in terms of gravitational acceleration with air resistance as follows:

$$[d^2y/dt^2] = 9.8 - b_1[dy/dt]^2, \qquad (1)$$

where y is the position on the vertical axis, b_1 is a damping coefficient, and 9.8 is the gravitational acceleration. The impact portion of the trajectory was modeled as an extremely stiff spring with energy dissipated through a linear damping term as follows:

$$[d^2y/dt^2] = -[k/m]y - b_2[dy/dt], \qquad (2)$$

where k is the stiffness, m is the mass, and b_2 is the damping coefficient. The model switched to and from this second equation when the position of the spring passed that of the constraint surface.

The model of the hand-guided spring event was somewhat more complicated. Linear mass springs have been used widely to model human limb movements (Berkinblit, Feldman, & Fukson, 1986; Bizzi, Chapple, & Hogan, 1982; Cooke, 1980; Hasan, Enoka, & Stuart, 1985; Kelso & Holt, 1980). However, human limb movements have also been found to take advantage of gravity by passively allowing gravity to move a limb through relevant portions of a trajectory (Mochon & McMahon, 1980, 1981). The hand-guided spring trajectories exhibited both types of motion. A

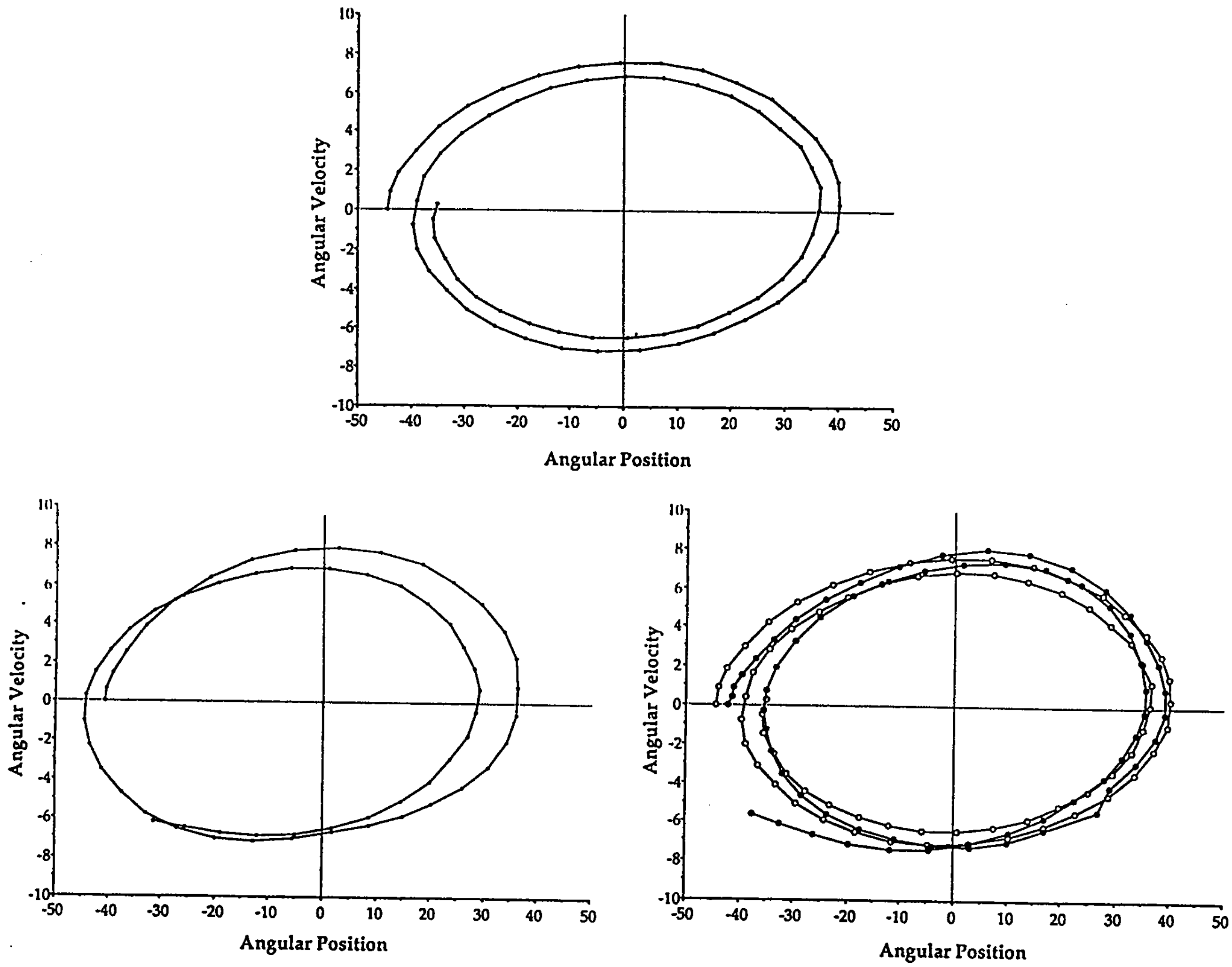

Figure 5. Top panel: Phase trajectory for the freely swinging pendulum in terms of angular position and angular velocity. Lower left panel: Phase trajectory for the manually guided pendulum display. Lower right panel: Comparison of phase trajectories for the freely swinging pendulum (open circles) and the manually guided pendulum (filled circles).

Table 4
Frequencies of Displays Judged as Natural Motion or as Moved by Hand

	Judged					
	Free fall and bounce			Free-swinging pendulum		
Actual	Natural motion	Hand	Total	Natural motion	Hand	Total
Natural motion	170	26	196	159	112	271
Hand	46	190	236	57	104	161
Total	216	216	432	216	216	432

free-fall equation was used to model the upper portion of the downward movement, switching to a mass spring for the lower portion up to and following the impact. Significantly, the manual trajectories could not be modeled without introducing a change in the stiffness between the falling and rising portions of the trajectory. The third part of the hand-guided spring model, capturing the inelastic impact, only applied to positive velocity values at the position of impact (i.e., generating the straight line trajectory above the zero-velocity axis). By definition, inelastic impact provides no rebound energy. Thus, the spring used to model human limb movement operated as soon as the trajectory reached zero velocity. This and the change in stiffness were direction-specific controls, and the need for such controls was a reflection of the spatial asymmetry of the modeled trajectories. The spatially symmetric trajectory of free fall and bounce did not require such changes.

The freely swinging pendulum was modeled as follows:

$$[d^2\theta/dt^2] = (9.8 \sin\theta)/l - b[d\theta/dt], \quad (3)$$

where θ is angular position, l is length, b is a damping coefficient, and 9.8 is the gravitational acceleration. To model the hand-moved pendulum, we adopted a nonlinear limit-cycle model developed by Bruce Kay to model responses of limb movements to perturbation (Kay, 1986; Kay et al., 1987; Kay, Saltzman, & Kelso, 1991). The model produces single-orbit limit cycles that are free of fluctuations aside from externally applied perturbations. Fluctuations observed in actual limb motions produce an elliptical band inside of which a trajectory wanders. As shown by Kay et al. (1991), the fluctuations can be modeled by stochastic variation of dynamical parameters within a limited range of values. Trajectories exhibit a limit-cycle stability in response to such self-induced perturbations. To model the hand-guided pendulum, the nonlinear model was modified to include stochastic variation in the stiffness and damping coefficients. The model was as follows:

$$[d^2\theta/dt^2] = -[k/m]\theta - (b_1 + b_2[d\theta/dt] + b_3\theta^2)[d\theta/dt], \quad (4)$$

where θ is angular position, k is stiffness, m is mass, and b_{1-3} are damping coefficients. The values of both k and b_2 were varied every Δt about mean values according to a Gaussian distribution.

Using these four models and a fourth-order Runge-Kutta algorithm, position data simulating each of the four modeled trajectories were generated. These were filtered and differentiated, as were the original trajectories. The respective simulations appear in Figure 6.

The significant property of the models of the hand-guided trajectories was that both models required elements that injected energy lost to dissipation back into the movement. In the hand-guided spring model, the energy lost in the inelastic collision was injected back into the movement through the change in stiffness of the mass-spring. In the hand-guided pendulum model, the energy lost through damping was injected back into the movement through the nonlinear damping term. The energy in the inanimate spring and pendulum events could only decrease because of frictional forces. In contrast, the energy in the corresponding animate events may have increased at times, revealing their animate character. (The distinguishing property of muscles as force generators is, of course, that they are autonomous energy sources.) We computed the energy trajectories in each of the events to investigate this possibility.

The momentary mechanical energy (E) is computed as the sum of the instantaneous kinetic energy (KE) and potential energy (PE) (Rosenberg, 1977), where

$$KE = \frac{1}{2} m\, v^2 \text{ and } PE = -\int F\, dx. \quad (5)$$

The potential energy function depends on the nature of the forces involved. We derived formulas to compute the mechanical energies in the spring and pendulum events as follows:

$$\text{Event 1: } E = \frac{1}{2} m\, v_y^2 + m\, g\, y \quad (6)$$

$$\text{Event 3: } E = \frac{1}{2} I\dot{\theta}^2 + m\, g\, l[1 - \cos\theta] \quad (7)$$

Using these relations, we computed the energy trajectories in each of the events. As can be seen in the top panel of Figure 7, energy only decreased for the free-fall and bounce events, most of it lost during the elastic rebound. In contrast, energy increased significantly during portions of the hand-guided spring events. As previously deduced, the early portion of the downward movement stayed close to the free-fall trajectory. Subsequently, however, the hand-guided trajectory deviated, showing distinct energy increases followed by a complete loss of energy in an inelastic collision, followed in turn by a steep energy increase.

Likewise, the manually guided pendulum trajectories, appearing in the lower panel of Figure 7, exhibited pronounced energy increases, especially near the ends of the movement, where the trajectories crossed. A pattern of increasing overshoot followed by compensating undershoot can be seen in one of the trajectories. Deviations from strict monotonic decrease apparent in the freely swinging damped

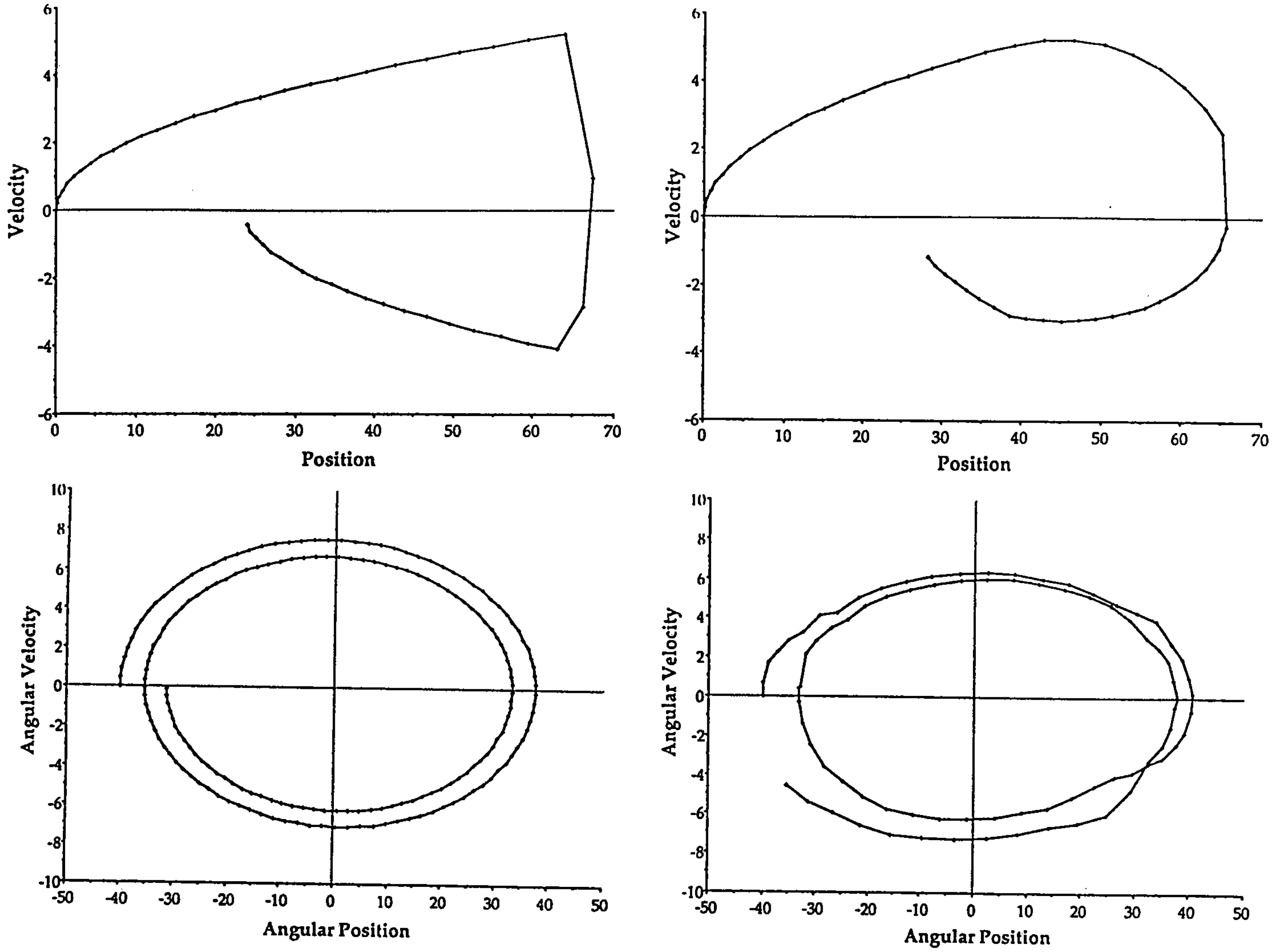

Figure 6. Simulated trajectories for the free fall and bouncing spring (top left), the manually guided spring (top right), the freely swinging damped pendulum (lower left), and the manually guided pendulum (lower right). The trajectories were generated by models described in the text. Compare these with the corresponding measured trajectories shown in Figures 4 and 5.

pendulum were introduced by measurement errors. The important point to note is that the fluctuations in the energy of the hand-guided pendulums were considerably greater than those produced by our measurement errors. Nevertheless, the fact that measurement error can produce significant variations in computed energy means that we must determine in future studies what form variations can be resolved reliably and used to detect differences in events.

In sum, this analysis revealed a single dynamic property, namely, increasing energy, which corresponded to animacy in both the spring and pendulum events. Despite the common dynamical property, the kinematic properties that might reveal the energy increases seemed to be different in the cases (i.e., more gradual acceleration after impact in the free-fall event and differences associated with crossing trajectories in the pendulum event). On the other hand, both involved perturbation of the position at which peak velocities occurred along the trajectories.

In the inanimate events, the peak velocities in each cycle occur at the positions where the motions would eventually settle at zero velocity (i.e., at the so-called "point attractors"). In general, increasing energy would correspond to the phase trajectories' spiraling outward from point attractors. A possible investigative approach, therefore, might be to discover the conditions under which outward spiraling might be detectable. Locally, outward spiraling can produce either increases in successive amplitudes of motion, or increases in velocity, or both, at corresponding points along a trajectory on subsequent cycles. Observers might well detect the former aspect and not the latter. Additional experimentation will be required to investigate these possibilities.

General Discussion

Runeson (1974) manipulated velocities along trajectories in displays using simple kinematic functions and asked observers to draw phase trajectories (i.e., plots of velocity

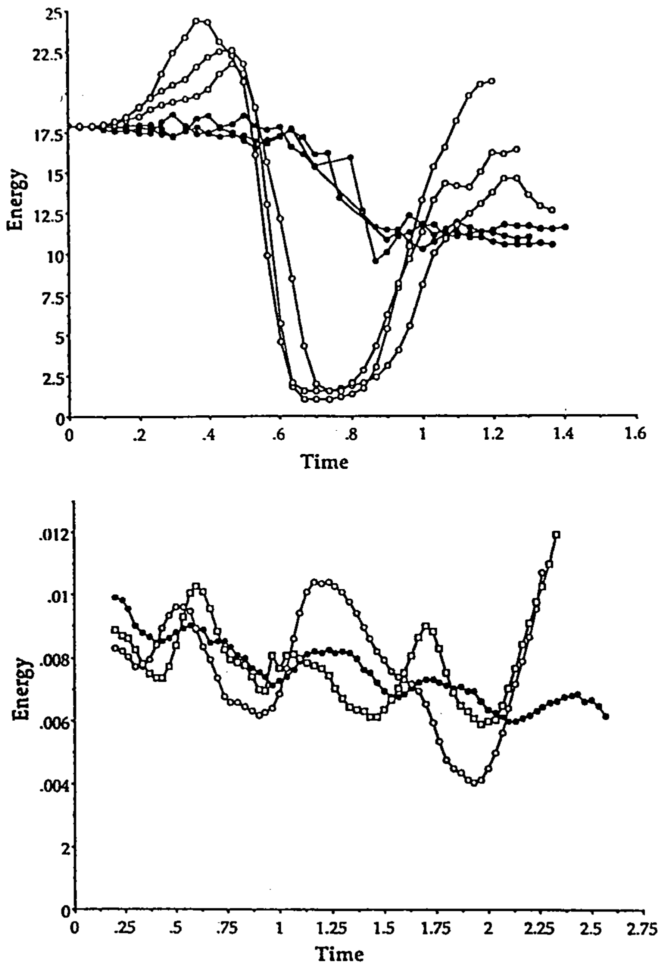

Figure 7. Mechanical energy trajectories computed from the measured kinematics. Top panel: Energy of the free falling (3 instances; filled circles) versus manually guided spring (3 instances; open circles). Lower panel: Energy of the freely swinging (1 instance; filled circles) versus manually guided pendulum (2 instances; open circles).

vs. position). Observers drew different graphs for each type of motion and were consistent in drawing the same graph each time a given motion was encountered, making it evident that they could recognize the motions. Nevertheless, the graphs that they drew were incorrect descriptions of the kinematics. Subsequently, Bingham and Runeson (1983) found that the same graphs were drawn when observers were given instructions to describe either *velocity* or *push.* One could not safely interpret the graphs using the semantics of either push or velocity because participants drew identical graphs despite the apparent semantic differences of the descriptors. Only the pattern of description could be used to discern perceptual capabilities. Accordingly, in the current study we have emphasized analysis of descriptive pattern and change in such pattern as evidence for the salience of changes in displays. But what of the perceptible significance of the displays? If one cannot rely on the semantics of perceptual reports, then where should one find a basis for interpretation?

Runeson (1977) advocated the use of dynamical models to guide investigation of kinematic properties as information in event perception. Direct manipulation of kinematics provides a poor basis for interpretation. For instance, Michotte (1963) inserted a brief delay at the point of contact between two objects in a simulated collision display. Although it was clear to Michotte's observers that the display was no longer of a collision, the new identity of the event was rather elusive. Michotte called it *triggering,* implying perceived release of stored energy, but this possibility remained vague and unverified. Another illustration of this problem is Todd's (1983) attempt to discover the information for recognizable types of bipedal gaits. He manipulated the kinematics of a simulation with 7 degrees of freedom without attention to the underlying dynamics of bipedal locomotion, and as a result he became rather lost in the sea of possibilities allowed by the 7-*df* system. His results demonstrated that perturbation of the actual (digitized) kinematics of locomotion affected the identifiability, but he was unable to show how or why this was so.

To avoid these difficulties, dynamical models of events can be used to generate simulated event displays. This is the strategy that has been used, for instance, in studies on the perception of collision events (Gilden & Proffitt, 1989; Todd & Warren, 1982; Runeson & Vedeler, 1993). The advantage is complete control over the dynamically determined content of the displays so that the physically lawful nature of the events is well specified. The disadvantages, however, are twofold. First, if the resulting perceptual judgments are poor, the question remains of whether the results revealed more about the perceptual system or about the inadequacies of the dynamical model used to generate the displays (Flynn, 1993, 1994). This difficulty is exacerbated by the second problem. Good models of complex events are difficult to derive. Most studies (thus far at least) have used the simplest models of the events under study, using simplifying assumptions such as no friction and no gravity (e.g., horizontal planar motion on an air hockey table). Until the potential sensitivity to the perturbations necessarily entailed by these simplifications has been determined, negative conclusions about general abilities to use motion to recognize given types of events are premature. More important, events involving complex dynamics have not been studied using simulations.

An advantage in using the patch-light technique is that the motions can be guaranteed to be those actually generated in an instance of the type of event under study. The attendant disadvantage, of course, is that the content of the display cannot be controlled absolutely.[6] The dynamics can be studied, nevertheless. We investigated event dynamics by applying methods that have been developed and used to study human motor behavior. The kinematics of the event were measured directly from patch-light displays (Bingham, 1987b) and compared with those generated using dynamical models. Our results now provide a context motivating

[6] On the other hand, the constraints exerted by actual events are instructive because we wish to reveal just those aspects of an event that are impossible to alter without obvious change of identity.

and constraining subsequent studies in which simulations can be used to manipulate the dynamics of the displays parametrically.

We showed that observers can identify a variety of events from motions and that the relative patterns of description reflect the underlying types of dynamics represented by the events including distinct types of nonrigid motion. Further, we found that changes in the orientation of the kinematics with respect to gravity altered the relative patterns of description and, by inference, the perceived character and identity of some events. The results support the notion that the underlying dynamics contribute to the perceptible significance of detectable forms of motion. That trajectory forms are a potentially important source of visual information was shown by the fact that motions of only a single patch were often sufficient to allow observers to recognize animate as opposed to inanimate versions of otherwise similar events. We reproduced the differences in trajectory forms through dynamical models and discovered that models of animate trajectory forms required energy injection, whereas models of the inanimate trajectories did not. Following this lead, we examined the mechanical energy flows computed from the oriented position and velocity data in each event and found that the animate events exhibited marked energy increases along portions of the trajectories, whereas inanimate events did not. Further confirmation that the kinematic repercussions of such energy flows provide perceptual information about animacy in events will now require the application of simulation techniques for display generation and systematic psychophysical investigations of these trajectory forms. Similarly, we now know that various liquid motions can be recognized as can motions in air. Earlier studies showed that bending can be recognized as well as elastic deformations (Bassili, 1978). Systematic studies using dynamical simulation will be required to determine how these various nonrigid events can be distinguished and recognized.

References

Barzel, R., & Barr, A. H. (1988). A modeling system based on dynamic constraints. *Computer Graphics, 22,* 179–188.

Bassili, J. N. (1978). Facial motion in the perception of faces and emotional expression. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 373–379.

Berkinblit, M. B., Feldman, A. G., & Fukson, O. I. (1986). Adaptability of innate motor patterns and motor control mechanisms. *Behavioral and Brain Sciences, 9,* 585–638.

Bertenthal, B. I., Proffitt, D. R., & Cutting, J. F. (1984). Infant sensitivity to figural coherence in biomechanical motion. *Journal of Experimental Child Psychology, 37,* 213–230.

Bingham, G. P. (1987a). Dynamical systems and event perception: A working paper: Parts I–III. *Perception/Action Workshop Review, 2*(1), 4–14.

Bingham, G. P. (1987b). Kinematic form and scaling: Further investigations and the visual perception of lifted weight. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 155–177.

Bingham, G. P. (1995). Dynamics and the problem of visual event recognition. In T. R. Port & T. van Gelder (Eds.), *Mind as motion: Dynamics, behavior and cognition.* Cambridge, MA: MIT Press.

Bingham, G. P., & Runeson, S. (1983, October). *On describing what is perceived: Seeing "velocity" versus seeing "push" in moving objects.* Presented at a meeting of the International Society for Ecological Psychology, Hartford, CT.

Bizzi, E., Chapple, W., & Hogan, N. (1982). Mechanical properties of muscles: Implications for motor control. *Trends in Neuroscience, 5,* 395–398.

Braunstein, M. L. (1988). The empirical study of structure from motion. In W. N. Martin & J. K. Aggarwal (Eds.), *Motion understanding: Robot and human vision* (pp. 101–142). Boston: Kluwer Academic.

Caramazza, A., McCloskey, M., & Green, B. (1981). Naive beliefs in "sophisticated" subjects: Misconceptions about trajectories of objects. *Cognition, 9,* 117–123.

Clement, J. (1982). Students' preconceptions in introductory mechanics. *American Journal of Physics, 50,* 66–71.

Cooke, J. D. (1980). The organization of simple, skilled movements. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 199–112). Amsterdam: North-Holland.

Cornilleau-Pézès, V., & Droulez, J. (1990). Three-dimensional motion perception: Sensorimotor interactions and computational models. In R. Warren & A. H. Wertheim (Eds.), *Perception and the control of self-motion* (pp. 81–100). Hillsdale, NJ: Erlbaum.

Cutting, J. E., Proffitt, D. R., & Kozlowski, L. T. (1978). A biomechanical invariant for gait perception. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 357–372.

Dijksterhuis, E. J. (1961). *The mechanization of the world picture.* Princeton, NJ: Princeton University Press.

Feldman, A. G. (1980). Superposition of motor programs: 1. Rhythmic forearm movements in man. *Neuroscience, 5,* 81–90.

Feldman, A. G. (1986). Once more on the equilibrium-point hypothesis (λ model) for motor control. *Journal of Motor Behavior, 18*(1), 17–54.

Feldman, A. G., Adamovich, S. V., Ostry, D. J., & Flanagan, J. R. (1990). The origin of electromyograms: Explanations based on the equilibrium point hypothesis. In J. M. Winters & S. L-Y. Woo (Eds.), *Multiple muscle systems: Biomechanics and movement organization.* New York: Springer-Verlag.

Flynn, S. B. (1993, August). Physical vs. animated events in collisions. Presented at the *Seventh International Conference on Event Perception and Action,* Vancouver, Canada.

Flynn, S. B. (1994). The perception of relative mass in physical collisions. *Ecological Psychology, 6*(3), 185–204.

Gentner, D., & Stevens, A. L. (Eds.) (1983). *Mental models.* Hillsdale, NJ: Erlbaum.

Gibson, J. J. (1966). *The senses considered as perceptual systems.* Boston: Houghton Mifflin.

Gilden, D. L., & Proffitt, D. R. (1989). Understanding collision dynamics. *Journal of Experimental Psychology: Human Perception and Performance, 15,* 372–383.

Green, M. (1989, April). *Using dynamics in computer animation: Control and solution issues.* Paper presented at *"Mechanics, control, and animation of articulated figures,"* an interdisciplinary workshop sponsored by the National Science Foundation and the MIT Media Laboratory, Cambridge, MA.

Hahn, J. K. (1988). Realistic animation of rigid bodies. *Computer Graphics, 22,* 299–308.

Hasan, Z., Enoka, R. M., & Stuart, D. G. (1985). The interface between biomechanics and neurophysiology in the study of movement: Some recent approaches. *Exercise and Sport Sciences Reviews, 13,* 169–234.

H H. H. (1981). *Myocybernetic control models of skeletal muscle.* Pretoria: University of South Africa.

Hildreth, E. C., & Hollerbach, J. M. (1987). The computational approach to vision and motor control. In F. Plum (Ed.) *Handbook of physiology: Vol. 5. Higher functions of the brain, Part 2.* Bethesda, MD: American Physiological Society.

Hildreth, E. C., & Koch, C. (1987). The analysis of visual motion: From computational theory to neuronal mechanisms. *Annual Review of Neuroscience, 10,* 477–533.

Hogan, N., Bizzi, E., Mussa-Ivaldi, F. A., & Flash, T. (1987). Controlling multijoint motor behavior. In K. B. Pandolf (Ed.), *Exercise and sport sciences reviews* (Vol. 15, pp 153–190). New York: Macmillan.

Horn, B. K. P. (1986). *Robot vision.* Cambridge, MA: MIT Press.

Isaacs, P. M., & Cohen, M. F. (1987). Controlling dynamic simulation with kinematic constraints, behavior functions and inverse dynamics. *Computer Graphics, 21,* 215–224.

Jammer, M. (1957). *Concepts of force: A study in the foundations of dynamics.* Cambridge, MA: Harvard University Press.

Jansson, G. (1977). Perceived bending and stretching motions from a line of points. *Scandinavian Journal of Psychology, 18,* 209–215.

Jansson, G., & Johansson, G. (1973). Visual perception of bending motion. *Perception, 2,* 321–326.

Jansson, G., & Runeson, S. (1977). Perceived bending motions from a quadrangle changing form. *Perception, 6,* 595–600.

Johansson, G. (1973). Visual perception of biological motion and model for its analysis. *Perception & Psychophysics, 14,* 201–

Johansson, G. (1976). Spatio-temporal differentiation and integration in visual motion perception. *Psychological Research, 38,* 379–393.

Kay, B. A. (1986). *Dynamic modeling of rhythmic movements: Converging on a description of the component oscillators.* Unpublished doctoral dissertation, University of Connecticut, Storrs.

Kay, B. A., Kelso, J. A. S., Saltzman, E., & Schöner, G. (1987). The space–time behavior of single and bimanual rhythmical movements: Data and limit cycle model. *Journal of Experimental Psychology: Human Perception and Performance, 13,* 564–583.

Kay, B. A., Saltzman, E., & Kelso, J. A. S. (1991). Steady-state and perturbed rhythmical movements: A dynamical analysis. *Journal of Experimental Psychology: Human Perception and Performance, 17,* 183–197.

Kelso, J. A. S., & Holt, K. G. (1980). Exploring a vibratory systems analysis of human movement production. *Journal of Neurophysiology, 43,* 1183–1196.

McMahon, T. A. (1984). *Muscles, reflexes, and locomotion.* Princeton, NJ: Princeton University Press.

Michotte, A. (1963). *The perception of causality.* London: Methuen.

Miller, G. S. P. (1988). The motion dynamics of snakes and worms. *Computer Graphics, 22,* 169–173.

Mochon, S., & McMahon, T. A. (1980). Ballistic walking. *Journal Biomechanics, 13,* 49–57.

Mochon, S., & McMahon, T. A. (1981). Ballistic walking: An improved model. *Mathematical Bioscience, 52,* 241–260.

Moore, M., & Wilhelms, J. (1988). Collision detection and response for computer animation. *Computer Graphics, 22,* 289–298.

Nalwa, V. S. (1993). *A guided tour of computer vision.* Reading, MA: Addison-Wesley.

Pedhazur, E. (1982). *Multiple regression in behavioral analysis.* New York: Holt, Rinehart & Winston.

Platt, J. C., & Barr, A. H. (1988). Constraint methods for flexible models. *Computer Graphics, 22,* 279–285.

Rock, I. (1973). *Orientation and form.* New York: Academic Press.

Rosenberg, R. M. (1977). *Analytical dynamics of discrete systems.* New York: Plenum Press.

Runeson, S. (1974). Constant velocity—not perceived as such. *Psychological Research, 37,* 3–23.

Runeson, S. (1977). *On the visual perception of dynamic events.* Uppsala, Sweden: University of Uppsala.

Runeson, S., & Vedeler, D. (1993). The indispensibility of precollision kinematics for the visual perception of relative mass. *Perception & Psychophysics, 53,* 617–632.

Spence, J. T., Underwood, B. J., Duncan, C. P., & Cotton, J. W. (1968). *Elementary statistics.* New York: Appleton-Century-Crofts.

Stoffregen, T. A., & Riccio, G. E. (1988). An ecological theory of orientation and the vestibular system. *Psychological Review, 95,* 2–14.

Sumi, S. (1984). Upside-down presentation of the Johansson moving light-spot pattern. *Perception, 13,* 283–286.

Terzopoulos, D., & Fleischer, K. (1988). Modeling elastic deformation: Viscoelasticity, plasticity, fracture. *Computer Graphics, 22,* 269–278.

Thompson, J. M. T., & Stewart, H. B. (1986). *Nonlinear dynamics and chaos: Geometrical methods for engineers and scientists.* New York: Wiley.

Todd, J. T. (1983). Perception of gait. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 31–42.

Todd, J. T. (1984). The perception of three-dimensional structure from rigid and nonrigid motion. *Perception & Psychophysics, 36,* 97–103.

Todd, J. T., & Warren, W. H. (1982). Visual perception of relative mass in dynamic events. *Perception, 11,* 325–335.

Ullman, S. (1979). *The interpretation of visual motion.* Cambridge, MA: MIT Press.

Ullman, S. (1984). Maximizing rigidity: The incremental recovery of 3-D structure from rigid and nonrigid motion. *Perception, 13,* 255–274.

Ullman, S. (1988). The incremental rigidity scheme and long-range motion correspondence. In W. N. Martin & J. K. Aggarwal (Eds.), *Motion understanding: Robot and human vision,* (pp. 227–267). Boston: Kluwer Academic.

Wilhelms, J. (1987). Using dynamic analysis for animation of articulated bodies. *IEEE Computer Graphics and Applications, 7,* 12–27.

Wilkinson, L. (1989). *SYSTAT: The system for statistics.* Evanston, IL: SYSTAT.

Witkin, A., Fleischer, K., & Barr, A. (1987). Energy constraints on parameterized models. *Computer Graphics, 21,* 225–229.

Witkin, A., & Kass, M. (1988). Spacetime constraints. *Computer Graphics, 22,* 159–168.

Appendix A

Property List Used in the Circle Properties 48 Task

Circle the properties that apply:

Bounce
Brick
Hand-guided
Settling
Flexible surface
Hit
Rising
Moves all around
Flat surface
Launched
Hand-stopped
Pushed
Swing
Swirling
Spring
Follows a straight line
Cloth
Hand-started
Magnetic
Flow
Drop
Leaves
Elastic
Fall
Gravity
Windshield wiper
Inclined surface
Floating
Stretchy
Pulled
Stir
Sticking
Sinking
Bumpy surface
Wind
Suction
Metronome
Clay
Splash
Molasses
Pieces of paper
Machine
Ball
Air
Hopping
Blow
Liquid
Ledge

Appendix B

Property List Used in the Circle Properties 100 Task

Circle the properties that apply:

Bounced
Thrown
Impacted
Sinking
Molasses
Manually guided
Dropped
Propelled
Rotating
Spinning
Hit
Lifted
Caught
Kicked
Pulled
Whirlpool
Stirred
Rocks
Flowing
Splashed
Rod
Autumn leaves
Skipping
Chopped down
Follows a straight line
Human movement
Waves
Gravity
Magnetic
Cloth
Let go
Floating
Ball
Rolling downhill
Windshield wiper
Slowed down
Distorted
Pulled by string
Wind
Stopped
Liquid
Motor
Ripples
Stretchy
Hopping
Slowed to stop
Walking
Football
Hugged
Inverted pendulum
Upside down
Jumping
Water
Suction
Air
Speeded up
Leaves
Spring
Slow
Vortex
Metronome
Hill
Wheel
Elastic
Free falling
Swirling
Flat surface
Perturbed
Stick
Running
Waterfall
Steam
Handshaking
Sliding door
Motor oil
Released
Machine
Moved by hand
Ketchup
Poured
Launched
Jello
Yanked
Pendulum
Strange
Rolling
Blown
Held and released
Swinging
Braking
Inclined surface
Glass
Landing
Rising
Pushed
Surface of liquid
Crawling
Completely random
Digging
Folding

Received December 28, 1993
Revision received October 4, 1994
Accepted December 7, 1994 ■