Research Report

TIMING AND APPARENT MOTION PATH CHOICE WITH HUMAN BODY PHOTOGRAPHS

Maggie Shiffrar[1] and Jennifer J. Freyd[2]

[1]Rutgers University and [2]University of Oregon

Abstract—In demonstrations of apparent motion, observers typically report seeing motion along the shortest possible path between two sequentially presented objects Recent work has demonstrated that violations of this shortest path rule occur with realistic photographs of a human body displayed for sufficiently long temporal intervals when a longer path is more anatomically plausible than the shortest path The current set of experiments investigated the mechanisms by which information about biomechanical motion constrains apparent motion perception In Experiment 1, we demonstrated, first, that the availability of extra processing time does not simply—in and of itself—result in the perception of longer paths of apparent motion Second, we rejected the hypothesis that the perception of biomechanically correct paths of apparent motion depends on biologically appropriate velocities In Experiment 2, we discovered that the longer the motion path required to satisfy the biomechanical movement limitations of the stimulus, the longer the time needed to construct and therefore perceive that path These findings together suggest that additional processing time is necessary, but not sufficient, for interpolations of longer paths

The phenomenon of apparent motion illustrates clearly the constructive nature of visual perception In classic demonstrations of apparent motion, two stationary dots presented sequentially, under appropriate spatiotemporal conditions, are interpreted as a single moving dot While there are an infinite number of possible paths connecting any two points, observers tend to perceive only a single path of apparent motion Based on experiments using relatively simple stim-

uli, researchers have traditionally argued that observers are biased or constrained to perceive the shortest possible path of apparent motion (Burt & Sperling, 1981, Korte, 1915) Recently, a violation of this shortest path constraint was demonstrated using high-quality photographs of a human body in different poses (Shiffrar & Freyd, 1990) In this experiment, when subjects viewed two alternating photographs of a human model in different positions, the perceived paths of apparent motion changed with the temporal separation between the onsets of the two stimuli (i e , stimulus onset asynchrony, or SOA) At short SOAs, subjects tended to see the shortest motion path With longer SOAs, observers tended increasingly to see longer apparent motion paths These longer perceived paths were of a very specific type, that is, they were those paths consistent with normal movements of the human body This finding, in conjunction with control studies, supports the hypothesis that when given enough time, the visual system constructs paths of apparent motion that are consistent with the biomechanical limitations of the human body

Our proposal that certain types of form information may constrain the perception of apparent motion speaks directly to one of the most controversial current issues in cognitive neuroscience Are form information and motion information processed by independent pathways (DeYoe & Van Essen, 1988, Livingstone & Hubel, 1988)? Of particular interest in this report is the recent finding that these generally independent pathways, known as the "what" and "where" pathways, do converge in the superior temporal sulcus, or STS (Baizer, Ungerleider, & Desimone, 1991, Goodale & Milner, 1992) and that cells located in this region exhibit a very special behavior in that they are selectively responsive to precise combinations of biological forms and movements (Perrett, Harries, Mistlin, & Chitty, 1990)

The purpose of the current set of psy-

chophysical studies was to improve understanding of how biological motion is analyzed by the human visual system Given our earlier finding that the visual system requires more time for the perception of biomechanically feasible paths of apparent motion, we asked Why do observers perceive long, biomechanically correct paths of apparent motion at long temporal intervals?

EXPERIMENT 1

Perhaps observers simply and arbitrarily perceive long paths at long temporal separations Such an interpretation would possibly be supported by Korte's third law, which proposes that the optimal length of an apparent motion path increases with temporal separation (Korte, 1915) It has also been proposed that the visual system attempts to construct the most globally correct interpretation of apparent motion stimuli and that under some conditions, this computation requires extra time (Shepard, 1984) Is the perception of apparent motion with naturalistic stimuli simply a low-level process that selects increasingly long paths with increasing temporal intervals? Or is choice of apparent motion paths constrained by higher level, figurally based processes that select the most globally correct path possible within a given temporal separation? Another question is whether this requirement for extra processing time actually reflects a sensitivity to slower or more natural biological velocities That is, does biological motion require any particular velocities for the perception of biomechanically correct paths of apparent motion? Or is extra processing time required for biomechanically correct path computation independent of the perceived velocity?

To address these questions, we again used stimuli consisting of photographs of a human model in different poses In previous experiments (Shiffrar & Freyd,

Address correspondence to Maggie Shiffrar, Center for Neuroscience, 197 University Ave , Rutgers University, Newark, NJ 07102, e-mail mag@cortex rutgers edu

1990), such stimuli were designed so that biomechanically correct paths of motion were in conflict with the shortest possible paths. In this experiment, we added a set of stimuli in which the biomechanically correct path of apparent motion was also the shortest possible path. Would observers perceive longer paths of apparent motion with increasing SOAs, even though these longer paths were incompatible with the range of biomechanically plausible motions of the human body?

In addition, half-cycle presentations of human photographic stimuli were used to determine the importance of perceived velocity. This presentation method added extra processing time without affecting the velocity of motion between stimuli. Half-cycle presentations differ from full-cycle presentations in that the second interstimulus interval (ISI) is made so long that all percepts of motion are inhibited during this interval. Thus, in half-cycle presentations, apparent motion is perceived only during the first ISI, while apparent motion under full-cycle conditions is perceived during both the first and second ISIs. As a result, apparent motion is unidirectional during half-cycle presentations and the velocity in this direction is identical to that in the full-cycle displays.

Method

Subjects

Thirty-two University of Oregon students, naive regarding the experimental hypothesis, participated in this study for credit toward a class requirement.

Apparatus and stimuli

Stimuli were displayed with a Gerbrands four-field tachistoscope that was controlled by an IBM pc/xt. This apparatus was also used in Experiment 2. Pairs of full-color photographs of a human body in different positions were created by photographing a model who remained stationary except for the movement of a limb. The 12 pairs of stimuli were divided into two groups defined by whether or not the shortest possible path was the biomechanically correct path. Each of these groups contained both solidity- and joint-constraint stimuli (Shif-

frar & Freyd, 1990). Short-path-correct, solidity-constraint stimuli showed a limb moving about opposite sides of a portion of the model's body. These stimuli included translation of an arm through a hole created by placing the model's other arm on her head, translation of a closed fist through a hole created by placing the model's other hand on her hip, and rotation of an arm beneath the bent leg of the model in a kneeling position. A sample solidity-constraint stimulus is shown in Figure 1. The joint-constraint stimuli in which the shortest path was correct showed movement about one of the model's joints. These stimuli consisted of photos showing rotation of a foot about the ankle, rotation of an arm about the elbow, and rotation of a bent leg about the knee. The remaining six pairs of stimuli were a subset of those we used previously (Shiffrar & Freyd, 1990) and were designed so that the shortest path was anatomically impossible. The solidity-constraint stimuli included movement of a closed fist about the head, ventro-dorsal movement of an open hand about the head, and dorso-ventral movement of one leg about the other leg. The joint-constraint stimuli included rotation of the fingers of the right hand about the wrist, rotation of the head about the neck, and rotation of the straightened right arm about the shoulder.

There were two possible temporal arrangements. (The stimuli were presented either in a full cycle, such that both the first and the second ISIs were equal, or in a half cycle, in which the second ISI was always 1 s. The visual field during the first and second ISIs was black. No apparent motion could be seen during

the second ISI in the half-cycle condition.

Procedure

Each subject sat in front of the tachistoscope and placed his or her head against a visor. Subjects were told that they would observe some rapidly flashing pictures of a model in different poses for as many cycles as they desired and that sometimes during these flashes they might see a kind of motion. They were also told that sometimes the path of motion would appear very clear, while other times they might see multiple paths or no motion. Subjects were asked to indicate the path(s) of this motion, if any, for each SOA level, using diagrams on an answer sheet.

The experiment was conducted using a between-subjects, 2 (timing: full or half cycles) × 2 (correct path: shortest or long) factorial design. Different subjects were run for each of the four cells (short correct path, full cycle; short correct path, half cycle; long correct path, full cycle; and long correct path, half cycle). Every subject observed a set of the six pairs of stimuli (three joint- and three solidity-constraint tests) at six different SOA levels during one session. Presentation order was randomized between subjects. For all of the photo pairs, the shortest SOA was 150 ms, consisting of a 100-ms stimulus duration (SD) and a 50-ms ISI. The remaining five SOA levels were constructed by adding 50 ms to both the SD and the ISI at each level. These SOAs were chosen because they yielded the best apparent motion across observers in pilot studies. Half of the subjects observed each stimulus at SOAs
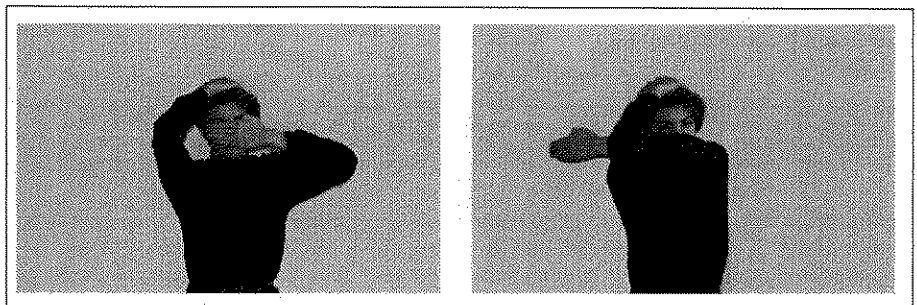

Fig. 1. Black-and-white rendition of a pair of color photographic stimuli used in Experiment 1. This solidity-constraint pair demonstrates a case in which the shortest possible path of motion is the biomechanically correct path. An equal number of joint-constraint, short-path-correct stimuli were used.

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increasing in magnitude, and the other half of the subjects observed stimuli at SOA levels of decreasing magnitude

Results and Discussion

For each subject and condition, we counted the number of times a particular path was chosen at each SOA level The results, shown in Figure 2, are consistent with the hypothesis that the visual system uses available time to choose the most correct path of apparent motion Since the pattern of results was identical for the joint-constraint and solidity-constraint stimuli, the data are collapsed across constraint type

When the shortest possible path of motion was the biomechanically correct path, subjects were significantly more likely to choose the short, biomechanically correct path than to choose the longer, biomechanically incorrect path at all six SOA levels in both the full- and

half-cycle conditions An analysis of variance (ANOVA) revealed no main effect for SOA level on the frequency of choosing the shorter path $F(5, 42) < 1 0$, $p > 50$ In the half-cycle condition, when the shortest possible path was biomechanically impossible, subjects perceived the long, biomechanically correct path of apparent motion across all SOAs An ANOVA revealed no main effect for SOA level on the frequency of choosing the biomechanically correct path, $F(5, 42) < 1 0$, $p > 50$ In the full-cycle condition, when the shortest path was biomechanically impossible, subjects became increasingly likely to perceive the long, correct path of apparent motion with increases in SOA, $F(5, 42) = 10 4$, $p < 01$ However, when the shortest path was the correct path in the full-cycle condition, subjects consistently reported seeing the shortest path of motion across all six SOA levels, $F(5, 42) = 2 01, p < 05$

The availability of extra processing time appears to be used by the visual system to compute the most correct, and not necessarily the longest, path of apparent motion Thus, these data are not consistent with the hypothesis that observers perceive longer paths of apparent motion with longer temporal separations While sufficient processing time may be required for the utilization of biomechanical constraints in apparent motion perception, the availability of this processing time does not, in and of itself, result in the perception of long paths These data also suggest that the availability of processing time during the second ISI is sufficient for the perception of globally consistent paths of apparent motion As a result, we can reject the hypothesis that a particular velocity is needed for the perception of biomechanically correct paths of apparent motion

EXPERIMENT 2

Experiment 1 suggests that perception of apparent motion paths with naturalistic stimuli can be described as an "intelligent" process that selects the most globally consistent image interpretation at long temporal intervals and that the availability of time after the second SD is sufficient to produce this effect However, a fundamental question remains Why is extra processing time needed for the perception of long, biomechanically correct paths of apparent motion?

Various theories have been advanced to account for the influence of temporal frequency on higher order constraints on apparent motion One theory, originally proposed by Braddick (1980), invokes a dichotomy between low-level and high-level processing in apparent motion In this theory, intelligent, higher level processes require longer temporal intervals because accessing high-level knowledge takes time Low-level interpretations, occurring in short-range apparent motion, are not thought to depend on access to higher level information and therefore require less time An alternative theory, generalized from Shepard (1984), is that the visual system will attempt to construct a motion path that is as globally consistent as possible Sometimes such
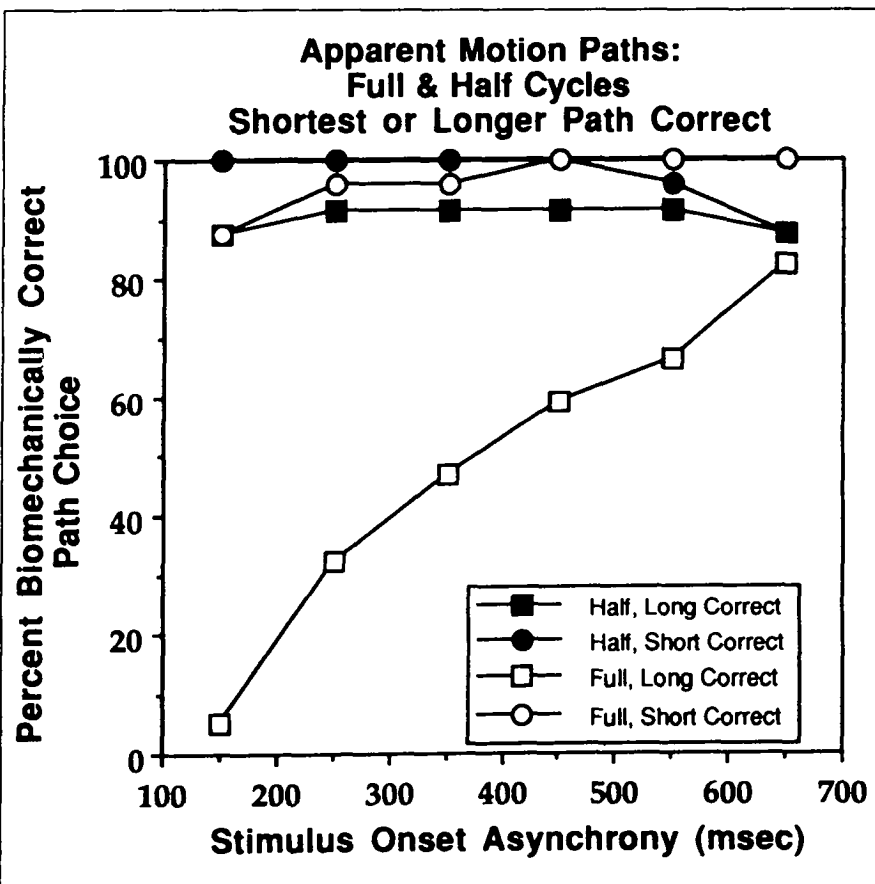

Fig. 2 Results from Experiment 1 The data in the full-cycle, long-path-correct condition were gathered in 1989

globally consistent solutions require longer paths, and interpolating longer paths requires more time.

To test these theories, we created a set of stimuli, again consisting of photographs of a human model, in which each pose was depicted in two different versions: a concise and a lengthy-distance version. The lengthy-distance version simply showed a relatively longer correct path than did the concise version of the same pose. If access to higher level information requires more time, then the absolute length of a path should be unimportant. That is, the same amount of time should be required for observers to perceive biomechanically correct motion paths for both the concise and the lengthy-distance versions of each stimulus pose. However, if long paths require more time to construct, then larger temporal separations should be required for the perception of biomechanically correct paths of apparent motion with the lengthy version of each pose relative to its concise version. That is, there should be a consistent shift toward greater temporal separations needed to perceive the lengthier biomechanically correct motions.

Method

Subjects

Eight University of Oregon students, naive regarding the experimental hypothesis, participated in this study for credit toward completion of a class requirement. None had participated in the first experiment.

Stimuli and procedure

As in Experiment 1, stimuli consisted of full-color photographs of the same model in different poses. There were 16 pairs of photos used, 8 joint-constraint stimuli and 8 solidity-constraint stimuli. Each stimulus type was further divided according to the length of the biomechanically correct path (see Fig. 3). The joint-constraint stimuli were thus made up of both a concise and a lengthy path for each of four different poses: rotation of the right arm about the elbow, rotation of the fingers of the right hand about the wrist, rotation of the foot about the ankle, and rotation of the body about the
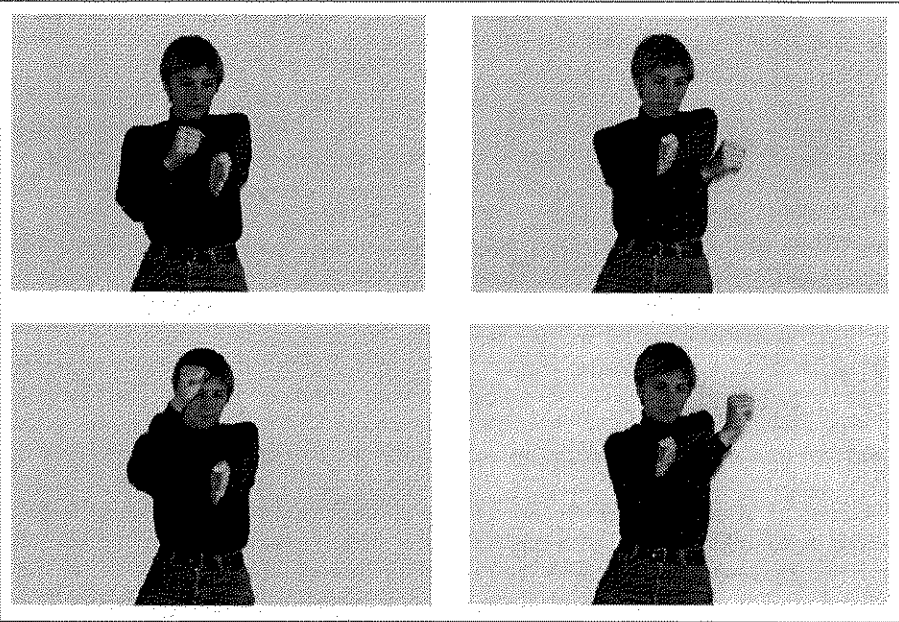

Fig. 3. Black-and-white renditions of a concise-distance pair (top) and the corresponding lengthy-distance pair (bottom) of color, solidity-constraint stimuli used in Experiment 2. Notice that for these stimuli, the absolute shortest path is biomechanically impossible.

waist. The solidity-constraint stimuli consisted of concise and lengthy paths for ventro-dorsal motion of the arm about the torso, lateral movement of the hand about the head, lateral movement of one foot about the other, and lateral motion of one arm about the other arm. Note that the shortest possible path was always biomechanically impossible.

The procedure was very similar to that of the full-cycle, long-path-correct condition in the first experiment. Subjects again indicated the perceived path of apparent motion on an answer sheet. The shortest of the six SOA levels used was 150 ms, and the longest was 650 ms. Unlike the first experiment, this experiment had a within-subjects design. The subjects saw either all of the concise-path or all of the lengthy-path stimuli first.

Results and Discussion

The results, shown in Figure 4, suggest that the requirement of additional processing time for the perception of long, biomechanically correct paths of apparent motion arises because longer paths require more time to construct. Again, the data are presented as the

mean percentage of trials during which the biomechanically correct path was chosen across different temporal separations. When the shortest path was biomechanically impossible, subjects became increasingly likely to perceive the long, correct path of apparent motion as SOA increased, for both the concise-distance stimuli, $F(5, 42) = 15.78$, $p < .01$, and the lengthy-distance stimuli, $F(5, 42) = 13.06$, $p < .01$. At the longest SOA level, subjects were significantly more likely to perceive the anatomically correct path of apparent motion with the concise-distance stimuli than with the lengthy-distance stimuli, $t(10) = 2.54$, $p < .05$.

The results of this experiment suggest that as the length of the most globally correct path increases, so does the amount of time needed for observers to perceive that path. By most globally correct path, we mean that path which satisfies the largest number of constraints.[1] Yet Experiment 1 revealed that time is

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1. A constraint is defined as an assumption about the nature of the physical world used by the visual system to solve the ill-posed visual problems. For further discussion, see Poggio, Torre, and Koch (1985).
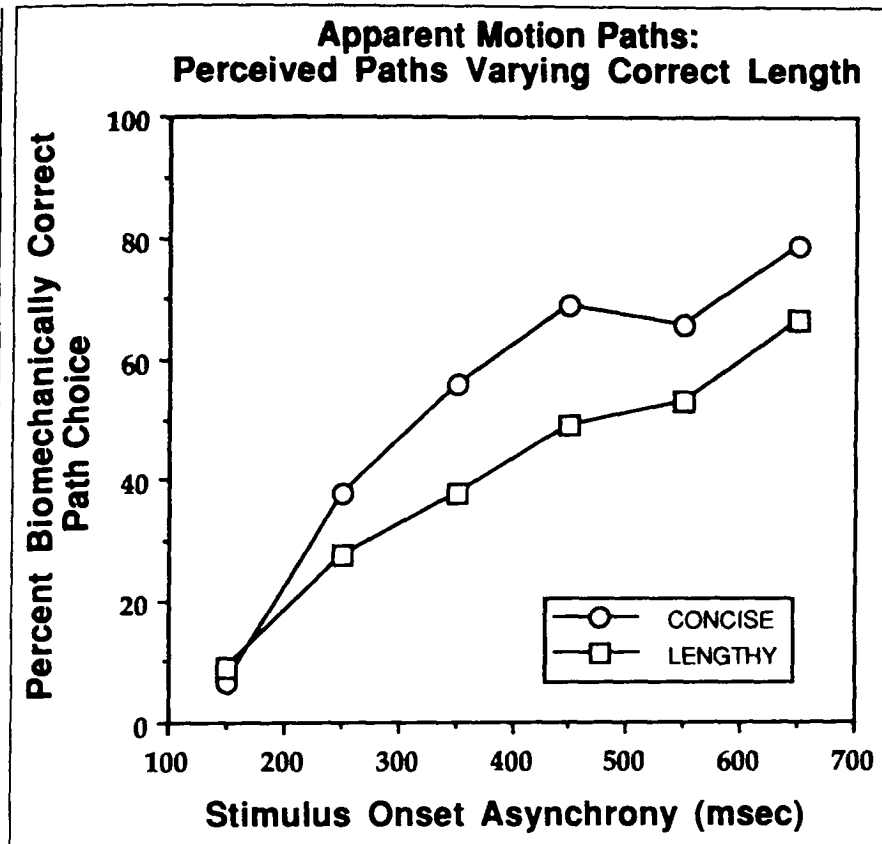
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Fig 4   Results from Experiment 2 The top line represents the results for the concise-distance stimuli, and the bottom line represents the results for the lengthy-distance stimuli

lengthier paths take longer to interpolate than do corresponding concise paths, does not contradict the possibility that time is needed also to access additional constraints Indeed, the interpretation of compelling biological motion displays may be a process that becomes increasingly constrained over time With minimal processing time, interpretations may be constrained by low-level assumptions of object permanence With increasing processing time, additional information regarding occlusion, rigidity, and biomechanical limitations may be invoked to further constrain image interpretation This hypothesis, which borrows heavily from the insightful proposals of Attneave's what–where connections in apparent motion (Attneave, 1974), awaits further research

Whether processing time is needed only for path interpolation or for both constraint access and path interpolation, this requirement of sufficiently long processing time for the correct perception of biological motion is consistent with other perceptual studies Consider, for example, Johansson's classic studies in which a vivid impression of human locomotion occurs with displays consisting of a group of moving dots corresponding to lights attached to the main joints of a human walker Interestingly, observers require approximately 200 ms of stimulus display before they can extract this biological motion (Johansson, 1976)

Given the need to accurately identify other animals' motion, such exquisite sensitivity to biological motion, as demonstrated by our results as well as those of Johansson, seems adaptive (Johansson, 1973, Shepard, 1984) These findings can also be considered in terms of Freyd's (1992, 1993) proposal that perceptual representations serve not only to track ongoing events, but also to anticipate the future by unfolding forward in time The current results suggest anatomical motion constraints may be used in order to adaptively anticipate the immediate future Anticipatory computations may thus reflect built-in assumptions of future motions that are particularly appropriate for animate creatures (Freyd & Miller, 1992)

Our results challenge the hypothesis that form and motion signals are always analyzed separately by the visual system (DeYoe & Van Essen, 1988, Livingstone

not sufficient to produce longer paths, instead, longer paths will be constructed only to the extent that they are globally meaningful Taken together, these results suggest that processing time is a necessary, but not sufficient, determinant of path length

GENERAL DISCUSSION

We set out to understand how the visual system interprets apparent biological motion Biological motion is particularly interesting because it often violates constraints of rigidity and shortest path lengths Our findings suggest that the availability of extra processing time by itself is not sufficient to promote the perception of longer paths of apparent motion Instead, the visual system selects paths of apparent motion that are as globally consistent as possible Moreover, at least for two-frame, or half-cycle, ap-

parent motion, the availability of processing time at the end of each cycle is sufficient to override the tendency to perceive the shortest possible path of apparent motion Thus, adequate processing time, rather than the presentation of a particular velocity, appears to be critical for the perception of biomechanically correct motion Finally, extra time may be necessary for the accurate interpretation of long paths of apparent motion with human body stimuli because longer paths require more construction time Taken together, we suggest that the visual system selects the shortest apparent motion path unless that path leads to an interpretation which is inconsistent with the biomechanical limitations of the human body If longer paths are needed to satisfy the constraints of human movement, then more time is needed to construct, and therefore perceive, these paths

Our finding from Experiment 2, that

& Hubel, 1988) Form and motion information were thought to be processed independently by the ventral and dorsal systems, respectively However, as noted earlier, the separation between these two systems may not be as distinct as initially thought, since both project to the STS, suggesting that this area may be the site of cooperation between these "what" and "where" systems (Baizer et al , 1991, Goodale & Milner, 1992) Consistent with this hypothesis, Perrett and his colleagues have identified numerous cells in the macaque STS that respond vigorously to moving primate figures and are unresponsive to moving inanimate control objects (Perrett et al , 1990) Thus, while form and motion information may be processed separately during lower levels of analysis, they appear to converge in the temporal cortex (and once form and motion information have converged, they may remain inextricably bound, Freyd, 1987, 1993) Perrett's elegant research suggests that this convergence may be particularly true for biological motion

While simple stimuli such as dots and lines may suffice for the study of low-level visual perception, more complex and meaningful stimuli may be necessary for the study of later stages of visual perception since later stages in the visual system receive more highly processed information What types of biological motion—and, indeed, whether any types of nonbiological motion—are able to trigger analysis by higher level, cooperative processing areas in the visual system is a question requiring further study

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