A capacity approach to kinematic illusions: The curtate cycloid illusion in the perception of rolling motion

Matthew I. Isaak
Department of Psychology
University of Calgary
misaak@acs.ucalgary.ca

Abstract

When a wheel rolls along a flat surface, a point on its perimeter traces a cycloid trajectory. However, subjects perceive the point's path not as the cycloid, but as the *curtate* cycloid, containing loops where the point contacts the surface. This is the *curtate cycloid illusion*. I hypothesize that the illusion occurs because the cognitive system does not have sufficient activation, or *capacity*, to both maintain an updated representation of the wheel's translation and compute its instant centers, the point about which the wheel is rotating at a given instant. This hypothesis is supported by showing that illusion susceptibility is decreased when the competing instant center demand is reduced, either by giving subjects practice at instant center computation (Experiment 1) or by eliminating the contour containing the instant centers subjects are most likely to compute (Experiment 2). Experiment 3 demonstrates that heightened instant center demands have less effect on illusion susceptibility when they are confined to irrelevant portions of the wheel's contour. A general form of the capacity account may explain illusions in the perception of many kinematic systems and point the way toward theoretical unity in the study of the perception of motion and events.

Our visual experience is filled with kinematic events, such as swinging pendulums and rolling wheels. Our perception and understanding of these events is as fallible as our perception of such static stimuli as the Muller-Lyer lines. For example, as a wheel rolls on a flat surface, a point on its perimeter follows a cycloid trajectory (top panel, Figure 1). Most subjects, however, draw or select the looped curtate cycloid (bottom panel, Figure 1) to represent the perimeter point's path (Isaak & Just, *in press*; Proffitt, Kaiser, & Whelan, 1990). This is the *curtate cycloid illusion*, or *CCI*. I survey previous approaches to kinematic illusions, introduce a capacity approach, then examine a capacity-based account of the CCI called the instant center hypothesis.

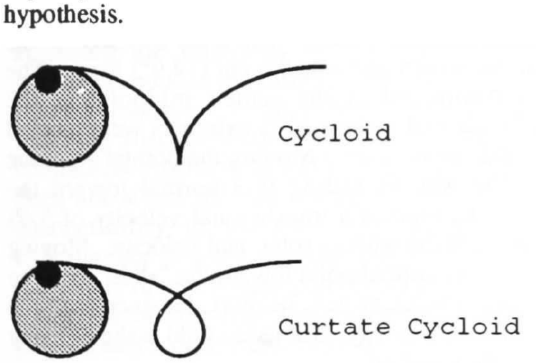

Figure 1: Stylized cycloid and curtate cycloid trajectories

Previous Approaches to Kinematic Illusions

The investigation of kinematic perception and comprehension has not been matched by the development of a unifying theory able to explain performance across stimuli, tasks, and subjects. Perceptual and cognitive researchers have worked in relative isolation from each other, using widely discrepant tasks and stimuli and grounding their explanations in vastly different schools of psychology.

Perceptual vector analysis (Johannson, 1986) states that objects' motions are perceived not only with respect to a static background, but also with respect to other objects' motions. The trajectories of a point on a rolling wheel's perimeter and one at its center may be described by a relative vector specifying the perimeter point's rotation about the wheel's center and a common translational vector representing the viewer-relative motion of both points. Johannson (1974) has not yet explained the susceptibility of many subjects to the CCI or the intersubject variability in it.

Coding theory (Restle, 1979) states that any motion may be described by different combinations of five parameters. The description with the fewest parameters gives rise to the perceived motion. Although coding theory can explain the CCI by claiming that the curtate requires fewer parameters for its description than does the cycloid, it does not explain how this variability depends on subject's spatial ability (Isaak & Just, *in press*).

Naive physics researchers (e.g., McCloskey, Caramazza, & Green, 1980) identify errors subjects make in understanding a kinematic system, then propose heuristics or mental models that might have produced the errors. One emerging result is that the neglect of some of a system's motion parameters leads to illusions or misconceptions. Naive physics theories have begun to explain the CCI by stating that a rolling wheel's translation is neglected in favor of its rotation (Proffitt et al., 1990). One problem with this approach is that plausible heuristics or models are often generated post-hoc to explain the results of a given study. Thus new models and heuristics tend to emerge with each new study.

A Capacity Approach to Kinematic Event Perception

Capacity theory is a general theoretical approach which suggests that the performance of cognitive tasks is constrained not only by the stimulus, but also by the amount of processing resources subjects have available and by the way subjects distribute the resources across the task environment. To date, capacity theory has been applied most fruitfully in linguistic domains, such as reading and speech perception. For example, the amount of processing resources subjects have available has been shown to influence the resolution of syntactic ambiguity (MacDonald, Just, & Carpenter, 1992). The capacity framework is an intuitively plausible theoretical lens through which to view language processing, because the sequential, serial nature of language imposes a continuous load on attentional and memorial processing resources.

Language, however, is not the only type of stimulus that occurs through time. Kinematic events also occur through time. To perceive and understand these events, observers must not only process and store the kinematic system's successive momentary states, but also integrate the states over time. Capacity theory suggests that a system's momentary states are processed, stored, and integrated in working memory using a finite supply of *activation* (Just & Carpenter, 1992). Because the supply is finite, an increase in either the storage or the processing requirements of one aspect of a motion causes the deallocation of activation from other aspects, which may be processed more slowly or lost from working memory. Capacity theory also proposes that individuals vary in the supply of activation. High-capacity individuals, with more activation, are less prone than low-capacity persons to processing slowdowns or the displacement of items from working memory when a task involves storing and computing multiple items.

An Instant Center Account of the CCI

The general capacity framework may be applied to the CCI by developing a specific, capacity-based process account of the illusion. The cycloid and curtate cycloid trajectories are distinguished mainly by their bottom portions: The curtate cycloid contains a loop, whereas the cycloid does not. Whether the trajectory contains a loop reflects how the wheel pivots when the perimeter point contacts and leaves the surface. To accurately derive the trajectory, the wheel's pivoting must be correctly processed when the point contacts the surface. Here, the point is the wheel's *instant center*, the point about which the entire wheel is rotating at that instant. One way subjects can correctly represent the bottom portion of the point's trajectory is to derive an instant center when the point contacts the surface. The CCI may arise when activation is deallocated from updating translation to computing the wheel's instant centers when the point contacts and leaves the surface. This deallocation begins only when the dot contacts the surface and continues until the dot reaches approximately seven or eight o'clock in its rotational path.

Three experiments investigated the instant center hypothesis. Susceptibility to the CCI was assessed by the degree to which a normally rolling wheel's translation was exaggerated in the attempt to make a perimeter dot follow a cycloid. Because the dot is already following a cycloid, subjects who exaggerate its translation must perceive the wheel as undertranslating and the dot's path as the curtate cycloid.

Experiment 1: Instant Center Practice Reduces Susceptibility to the CCI

Experiment 1 compares the effects on CCI susceptibility of practice at computing instant centers to the effects of experience with a task that does not involve instant center computation. Practice should reduce the demand imposed by instant center computation, increasing the activation available to update translation and reducing susceptibility to the CCI.

Thirty-six subjects viewed rolling wheels or tumbling batons. Trials occurred in blocks in which either only wheel or only baton trials were viewed. There were four block sequences, each viewed by nine subjects: wheel-wheel-wheel (WWW), baton-baton-baton (BBB), baton-baton-wheel (BBW), wheel-baton-wheel (WBW). Because continued experience with rolling wheels allows subjects to practice instant center computation, they should be less prone to the CCI on the third than on the first block of the WWW sequence. By contrast, they should be as prone to the CCI on the third as on the first block of the WBW sequence. The bottom portion of the path of a dot at one end of a tumbling baton may be derived by assessing the dot's horizontal displacement along the surface. If there is no displacement, the baton's translation/rotation ratio is 1:1, but if the dot slips forward or backward, the translation/rotation ratio is greater than or less than one, respectively.

Method

White wheel rims or batons (9.3° of visual angle) rolled or tumbled across a black computer screen. A small dot appeared on the inside of the wheel's rim or at one end of the baton. The objects rolled on a white band (width = 7.6° of visual angle) extending the width of the screen.

Subjects viewed 33 trials arranged in three blocks of eleven. The object's translation/rotation relationship was 1:1 on five of the trials in each block, overtranslating on three, and overrotating on three. On 1:1 trials, the wheel's rotational velocity was 0.38 rev/s, and its translational velocity was 5.65 cm/s (10.7°/s). On overrotating trials, the wheel's rotational speed was increased by factors of 1.15, 1.20, or 1.25. On overtranslating trials, its translational speed was increased by factors of 1.25, 1.35, or 1.50.

Subjects were shown a drawing of a cycloid and were instructed to change the motion until the dot's path matched the drawing if they did not think the dot was already following the cycloid. Subjects used a mouse button to move a pointer along a horizontal scale that controlled the wheel's translation/rotation ratio. The scale appeared in the top center of the screen and was 8.0 cm (14.9°) long . The pointer was positioned at the scale's midpoint at the beginning of each trial. The scale's extremes were labeled "more spin" and "more slide". Moving the pointer from the point where the wheel's rolling was normal toward the "spin" extreme maintained a translational velocity of 5.65 cm/s, but increased the wheel's rotational velocity. Moving the pointer from the normal point toward the "slide" extreme kept the rotational velocity at 0.38 rev/s, but increased the wheel's translational velocity. Subjects could make as many adjustments as they wished.

Results and Discussion

As expected, a practice effect occurred in the WWW condition (see Figure 2): Subjects performed more accurately on the third (mean = 1.11:1) than on the first block (mean = 1.21:1), t(8) = 2.52, $p < .05$. Also as predicted, subjects' performance in the third block of the WBW condition (mean = 1.19:1) was not reliably better than their performance in the first block (mean = 1.22:1), t(8) = 0.94, $p > .05$. To determine whether the WWW practice effect reflected decreasing susceptibility to the CCI or merely increasing strategic or motoric facility with the adjustment task, I examined the sensitivity with which subjects discriminated cycloid from curtate cycloid trajectories in the first and final blocks of the WWW and WBW conditions. Hits were defined as 1:1 trials on which subjects' final ratio selections ranged from 0.95:1 to 1.05:1. False alarms were defined as overrotating trials on subjects selected ratios less than 0.90:1. Here, subjects did not adequately adjust the motion of overrotating wheels toward 1:1, suggesting that they saw the dot's curtate cycloid path as the cycloid. Subjects more sensitively discriminated curtate cycloid from cycloid trajectories in the final block (mean $d' = 1.15$) of the WWW condition than in the initial block (mean $d' = 0.17$), t(8) = 2.63, $p < .05$. By contrast, subjects did not discriminate curtate cycloid from cycloid trajectories more sensitively in the final block (mean $d' = 0.38$) of the WBW condition than in the initial block (mean $d' = 0.12$), t(8) = 1.19, $p > .05$.

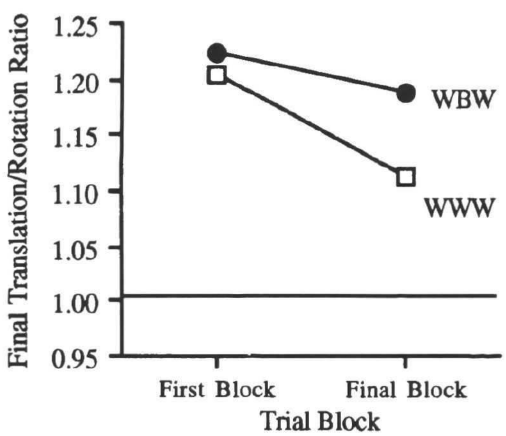

Figure 2: Final translation/rotation ratio in Experiment 1 as a function of the trial block and block sequence.

Experiment 1 yielded one main conclusion: Practice at adjusting the trajectory of a dot on a rolling wheel's perimeter reduces the instant center demand for activation, freeing resources to cumulate the wheel's translation and reducing susceptibility to the CCI. The practice effect contradicts Proffitt et al.'s (1990) suggestion that experience does not affect illusion susceptibility. That decreases in susceptibility to the CCI were found across a brief experimental session suggests that the CCI is more likely the result of temporary computational demands than the reflection of fundamental perceptual biases. Continued practice may reduce these demands.

Experiment 2: Instant Centers are Computed When the Dot Contacts the Surface

I claimed that the CCI arises when subjects compute instant centers besides the dot. The additional instant centers that are most likely computed are those immediately trailing the dot (Isaak & Just, in press). The portion of the wheel's contour trailing the dot is thus implicated in the CCI because it contains these additional instant centers. If trailing contour were absent, subjects would be less likely to compute trailing instant centers and would be less prone to the CCI.

Subjects viewed three types of rolling wheels: wheels in which the 45° of arc trailing the dot were deleted, wheels in which the 45° of arc leading the dot were deleted, and intact wheels. The CCI should be least apparent for wheels with deleted trailing arc.

Method

The method resembled Experiment 1 except as follows: Fifteen subjects viewed a random sequence of the three types of wheels. Each of the wheel types appeared on eleven of the experiment's 33 trials. The rolling motion was normal on five of the trials for each wheel type, overtranslating on three, and overrotating on three.

Results and Discussion

A main effect of stimulus type was found, $F(2, 26) = 9.01$, $p < .01$. Subjects were less prone to the CCI on trailing-deleted (mean = 1.02:1) than on intact (mean = 1.10:1), $F(1, 26) = 17.36$, $p < .01$ or leading-deleted wheels (mean = 1.08:1), $F(1, 26) = 7.76$, $p < .01$ (see Figure 3). Subjects were equally prone to the CCI on leading-deleted and intact wheels.

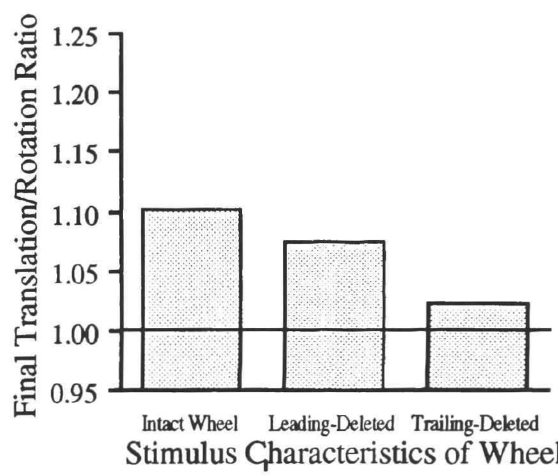

Figure 3: Final translation/rotation ratio in Experiment 2 as a function of the wheel type.

Experiment 2 yields two conclusions. First, the CCI arises when activation is diverted from translation cumulation to instant center computation when the dot contacts the surface. When we reduce the likelihood that these instant centers will be computed, activation is released, allowing the cumulation of translation and reducing susceptibility to the CCI.

Second, the cognitive conditions responsible for the CCI are short-lived. Instant centers are computed only when the dot is between 6 o'clock and about 7:30 in its rotation about the wheel's center. If instant centers were computed before the dot contacted the surface, deleting leading contour should have improved performance, as the leading contour contains the wheel's instant centers before the dot hits the surface. No improvement was found. If instant centers were computed after the dot passed 7:30 in its rotation, eliminating 45° of trailing arc should not have reduced susceptibility to the CCI as substantially as it did. The reallocation of resources from translation cumulation to instant center computation does not occur for a large portion of the total time that rolling motion is viewed, but rather for one-eighth or less of the total time on task.

Experiment 3: Instant Center Computation Impairs Translation Cumulation

Experiment 3 tests the notion that instant center computation consumes the activation allocated to translation processing rather than that dedicated to rotation processing. The wheel's rotation or translation was exaggerated during either the top or bottom portion of the dot's trajectory (from 11:30 to 2:30 or from 5:30 to 8:30, respectively, in its rotation around the wheel's center). The wheel's motion was normal when the dot was not passing through the selected portion of its path. Translational distortions should influence performance more when they occur in the bottom than in the top of the dot's path, and should influence performance more than rotational distortions should.

Method

Eighteen subjects viewed 27 randomly ordered trials. Distortions exaggerated the wheel's rotation on nine trials and its translation on nine. There was no distortion on the remaining trials. Rotational distortions decreased the wheel's translation/rotation ratio to 0.75:1, 0.80:1, and 0.85:1 on three trials each. Translational distortions increased the ratio to 1.25:1, 1.35:1, and 1.50:1 on three trials each. The distortions occurred during the top or bottom or throughout the dot's path; six different subjects participated in each of these conditions.

Results and Discussion

As predicted, there was an interaction between the nature of the distortion of a rolling wheel's motion and the location of the distortion in the dot's path, $F(4, 102) = 4.62$, $p < .05$. Subjects more accurately adjusted translational distortions when they occurred in the top (mean = 1:20:1) than when they occurred in the bottom of the dot's path (mean = 1.26:1), $F(2, 102) = 4.89$, $p < .05$ (see Figure 4). Rotational distortions were adjusted equally accurately regardless of location. These results demonstrate that instant center computation consumes the activation allocated to cumulating translation rather than that allocated to rotational processing.

Overall, subjects were more prone to the CCI when the distortions occurred in the bottom of the dot's trajectory (mean = 1.06:1) than when they occurred in the top of dot's path (mean = 1.03) or throughout the dot's path (mean = 1.01:1), $F(2, 102) = 3.86$, $p < .05$. The deallocation of activation to instant center computation occurs only when the dot is in the bottom of its trajectory.

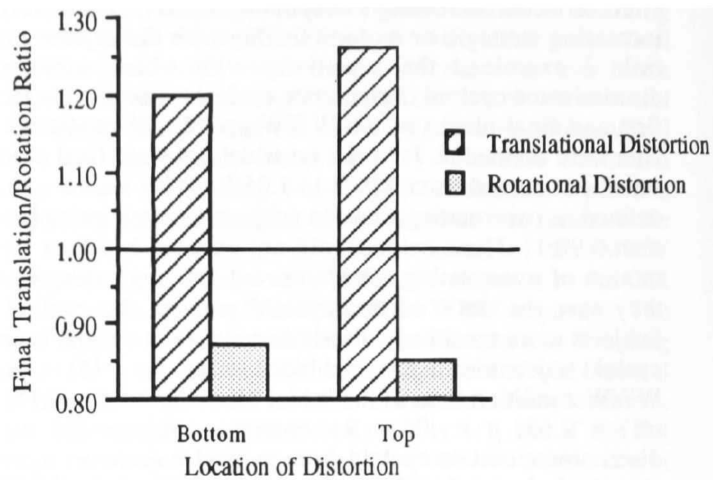

Figure 4: Final translation/rotation ratio choice in Experiment 3 as a function of the type and location of the distortion.

General Discussion

A capacity framework was used to develop an instant center account of the CCI. Although three experiments supported components of this account, a capacity view of the CCI was not explicitly contrasted with such approaches as perceptual vector analysis, coding theory, and naive physics. In my view, capacity theory does not directly oppose these approaches, but is instead a broader framework capable of incorporating aspects of the other approaches. Capacity theory may be instantiated as a comprehensive hybrid symbolic/connectionist model of mind in which productions manipulate the activation levels of representational elements. By contrast, perceptual vector analysis, coding theory, and naive physics may be seen as narrower hypotheses about the particular productions or representational elements likely to be important in a capacity model of kinematic thinking. The computation of perceptual vectors, for example, may be instantiated in productions manipulating the activation of direction perception units. Similarly, heuristics used in understanding a kinematic system may be coded as productions in a capacity model.

Finding General Mechanisms of the Neglect of Motion Parameters

The instant center hypothesis may be viewed as a task-specific component of a more general capacity account of kinematic illusions, which runs as follows: The accurate perception of many kinematic events requires the correct selection and efficient coordination of object and observer-relative frames of perceptual/cognitive reference. At critical points during the event, such as at motion discontinuities (Gilden, 1991), additional processing demands compel subjects to focus primarily on one reference frame, such as the object-relative frame, depleting the supply of activation and leading to a breakdown in the coordination of the reference frames and perhaps to the neglect of one of the motion parameters. Because attending to object-relative motions entails attending only to the portion of the display subtended by the object, whereas attending to observer-relative motions may entail attending to the entire field, object- and observer relative frames may correspond respectively to distributed and focused modes of attention, or to wide and narrow settings of the attentional zoom lens. Generally, subjects are adept at shifting between the object- and observer-relative frames, as moving between the narrow and wide attentional zoom lens settings typically requires less than 100 ms (Eriksen & St. James, 1986). Sudden events, however, such as stimulus onsets (Yantis & Jonides, 1984) and, perhaps, motion discontinuities, may capture attention in one or the other of the frames, causing the attentional zoom lens to become stuck on one setting. The processing that might have occurred through the other setting or frame is thus neglected, causing illusions or errors.

Extending the Capacity Account

A capacity account may be extended to kinematic systems other than rolling wheels. I suggest that capacity theory is most likely to explain illusions in events in which a) systematic errors are made on one kinematically relevant dimension, and b) the dimension on which the errors are made is itself kinematic, such as translation, rather than a static attribute such as mass distribution. The relative arrival-time configuration (Law, Pellegrino, Mitchell, Fischer, McDonald, & Hunt, 1993) fits these criteria. Two objects are seen moving at a constant velocity toward a destination, and the task is to state which object will arrive at its destination first. The correct answer depends on the relative velocity and distance-to-target of the two objects. Subjects neglect the relative velocity and base their answers primarily on relative distance. Capacity limitations might underlie the neglect of relative velocity, which becomes apparent only over time and thus entails integrating successive representations (Law, et al., 1993). Relative distance-to-target, by contrast, is apparent at each instant in time and requires no integration to process.

The capacity account may be generalized not only to kinematic systems other than rolling wheels, but also to populations other than college students, such as older adults. A reduction in capacity has been posited to account for age-related declines in cognitive performance (Salthouse, 1988). The decline in capacity may be more pronounced in spatial than in verbal tasks because older adults have accumulated a lifetime of experience with verbal materials, but usually have had little contact with spatial materials (Tubi & Calev, 1989). Salthouse and Mitchell (1989) found that age impaired the integration of new computations with old products more than the simple maintenance of products. I have suggested that such integrative processes are more strongly implicated in the perception of kinematic properties that change over time than in the perception of momentary kinematic states. Accordingly, Scialfa, Guzy, Leibowitz, Garvey, & Tyrell (1991) found that older adults were less sensitive than their younger counterparts to vehicular accelerations and decelerations, but were equally accurate at estimating absolute velocity. Together, these suggestions imply that older adults may be more susceptible to the CCI than younger adults, and that older adults may be more impaired relative to younger adults at processing a rolling wheel's translation than at processing its rotation.

Implications for the Relationship between Perception and Cognition

I stated earlier that perceptual and cognitive researchers in the field of kinematic event perception have worked in relative isolation from each other. The current research may be seen as containing elements of both the perceptual and cognitive approaches to kinematic event perception. Reflecting a cognitive influence, the research investigated the influence of a higher-level variable, working memory capacity, on susceptibility to the CCI. Reflecting a perceptual influence, susceptibility to the CCI was assessed by examining how well subjects adjusted a wheel's motion so that a perimeter dot followed a cycloid: This procedure resembles the nulling procedure used in psychophysical research, in which illusion magnitudes are quantified by requiring subjects to adjust a test stimulus so that it matches a standard stimulus along some dimension.

Because the present research examines the effects of cognitive factors on lower-level perceptual processes, it makes the implicit claim that low-level perceptual processes, often thought to be relatively immutable within subjects and invariable across subjects, may in fact be susceptible to substantial top-down influences. In the extreme, this claim suggests that the phenomena usually studied by psychophysicists such as illusions of form, luminance, or motion, may be subject to modulation by the factors usually considered the province of cognitive scientists.

Although there has been relatively little investigative interaction between psychophysicists and cognitive scientists, several pieces of evidence, primarily from the psychophysical literature suggest that cognitive variables may influence susceptibility to dynamic illusions usually thought to reflect low-level perceptual and neural processes. Studies by Chaudhuri (1990) and Shulman (1991) demonstrate that attention may modulate the motion aftereffect. The motion aftereffect occurs when a static or ambiguously moving stimulus appears to move in a direction opposite to the motion of a stimulus to which the subject has been adapted. The neural locus of the motion aftereffect is thought to be in MT (Chaudhuri, 1990). Chaudhuri found that the magnitude of the aftereffect was reduced when subjects' attention was displaced from fixation. Shulman's subjects attended to either of two simultaneously presented squares rotating in depth. The rotation of a subsequent, ambiguously rotating square then appeared opposite in direction to the motion of the square to which subjects had attended previously. These results suggest that processing in MT may be amenable to attentional influence.

Hikosaka, Miyauchi, and Shimojo (1993) presented a new illusion, the line-motion illusion, in which a line segment, although presented all at once, appeared to spread from one extremity if attention was selectively drawn to that extremity. Hikosaka et al. suggested that attention acts to accelerate visual processing at particular locations, making stimuli appearing at that location seem to occur slightly before stimuli appearing at other locations. This hypothesis implies that attention may influence processing in low-level motion detection areas of the brain, such as V1.

These studies demonstrate that basic perceptual phenomena, such as aftereffects of adaptation to motion, may be subject to cognitive mediation, just as the current research showed that susceptibility to the CCI may depend on the supply of processing resources subjects have available. The discovery of the cognitive mediation of such processes adds both clarity and further complexity to the intricate picture of such processes yielded by traditional perceptual and psychophysical investigations. For example, the discovery that attention may modulate motion aftereffects might suggest either that the brain areas implicated in motion processing contain inputs from brain areas implicated in attention, or that attention exists at every level of processing -- even V1 -- as a pattern of activation across processing units. Although the current research differs from the above examples in that it derives more from a cognitive than a psychophysical perspective, it joins these other investigations in showing that the relatively unexplored perception/cognition interface may prove a vital thread for future investigators attempting to delineate the rich tapestry of processes comprising our perception and comprehension of such seemingly basic components of the world around us as light, form, and motion.

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