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The Curtate Cycloid Illusion: Cognitive Constraints on the Processing of Rolling Motion

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Abstract

When a wheel rolls along a flat surface, a point on the wheel's perimeter follows a cycloid trajectory. Subjects, however draw the curtate cycloid, characterized by bottom loops, rather than the cycloid to depict the path that a point on a static wheel's perimeter would trace if the wheel were rolling. This is the *curtate cycloid illusion*. In Experiment 1, we show that animating the wheel does not dispel the illusion and that subjects high in spatial ability are less susceptible to the illusion than are low-spatials. Experiments 2, 3a, and 3b supported the hypothesis that the illusion occurs when subjects reallocate cognitive resources from processing a rolling wheel's translation to computing its instant centers, the point about which the wheel is rotating at a given instant in time. This reallocation occurs only when a reference point on the wheel's perimeter contacts and leaves the surface. We conclude that the illusion does not reflect fundamental perceptual biases, but rather stems from transient shortages of cognitive resources during the higher-level processing of the wheel's translation and rotation.

This paper examines an illusion in the perception of rolling motion. A point on a rolling wheel's perimeter follows a cycloid trajectory (see Figure 1). Subjects rarely draw the cycloid to depict the path that a point on a static wheel's perimeter would trace if the wheel were rolling. Instead, they modally draw the curtate cycloid trajectory, characterized by bottom loops (Proffitt et al., 1990; see Figure 1).

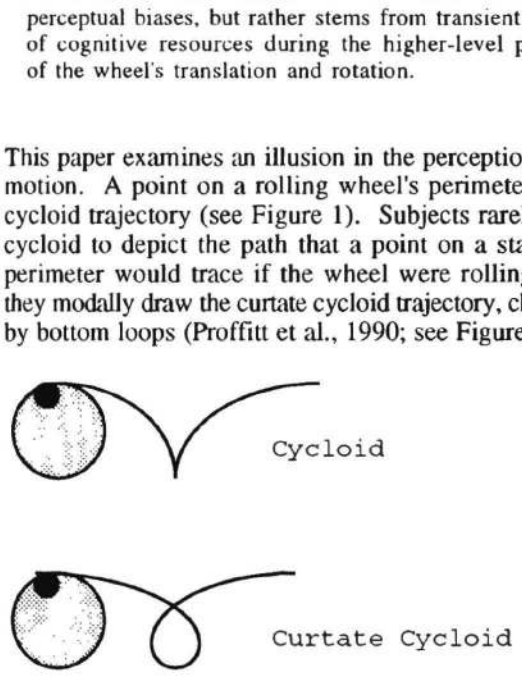

Figure 1: Stylized cycloid and curtate cycloid trajectories

The tendency to imagine or perceive the path of a point on a rolling wheel's perimeter as the curtate cycloid will be called the *curtate cycloid illusion*, or CCI. This paper examines the effect of animating the wheel's rolling on susceptibility to the CCI, explores possible individual differences in susceptibility to the CCI, and provides a processing explanation of the CCI.

If the CCI occurs because subjects have trouble processing mental animation, it should vanish when animated rolling wheels are viewed. If, however, the CCI stems from higher-level processing of motions such as rotation and translation, it should occur even when the wheels are animated. Subjects cannot accurately adjust a rolling wheel's translational speed to correspond to its rotational speed (Vicario & Bressan, 1990) or match animated trajectories with the points on a static wheel that would produce them during rolling (Proffitt et al., 1990). Animating whole wheels may help subjects dissociate the motions of points from the motions of objects.

If the CCI reflects a fundamental bias in the perceptual system, there should be few individual differences in susceptibility to the CCI. Experience with and knowledge of rolling wheels do not reduce susceptibility to the CCI (Proffitt et al., 1990). There may be another source of individual differences in susceptibility to the CCI, however: cognitive resource limitations. *High-capacity* individuals have more processing activation available than *low-capacity* individuals to store and compute information in working memory. High-capacity individuals can better integrate different types of information during the performance of a task than can low-capacity persons. High-capacity individuals are also less prone to processing slowdowns and forgetting than are their low-capacity counterparts.

Because rolling consists of both rotation and translation, it may impose a large demand on limited cognitive resources. Individual differences in the availability of cognitive resources may be reflected in individual differences in susceptibility to the CCI. Individuals with more resources available may better process and store both a rolling wheel's translation and its rotation. They may thus be less subject to the CCI than individuals with fewer resources available. Analogously, the ability to determine which of two moving objects will first reach its destination depends on the ability to integrate the objects' relative distance and relative velocity, which in turn depends on the amount of cognitive resources subjects have available (Law, Pellegrino, Mitchell, Fischer, McDonald, & Hunt, 1993).

In our experiments, individual differences in available cognitive resources were assessed psychometrically with the Space Relations Test, or SRT (Bennett, Seashore & Wesman, 1972). On the SRT, subjects must select the correct folded depictions of diagrams of unfolded objects.

The SRT assesses an ability called *spatial visualization*. Individual differences in spatial visualization arise because visualization imposes simultaneous processing and storage demands (Salthouse, Babcock, Mitchell, Palmon, & Skovronek, 1990), taxing some subjects' supply of spatial processing resources. Subjects scoring poorly on the SRT should be more prone to the CCI.

The CCI may arise because the wheel's rotation is processed at the expense of its translation (Cutting & Proffitt, 1981). The curtate cycloid's bottom loop, in which the dot appears to move backward when it contacts the surface, is a plausible consequence of lagging mental translation. It has not been demonstrated that the neglect of a rolling wheel's translation actually produces the CCI, nor has it been demonstrated exactly how translational neglect might produce the curtate cycloid's bottom loop. The translational neglect hypothesis is thus a potential component of a process account of the CCI, rather than a complete explanation of the illusion. We offer a processing account of the CCI after Experiment 1. Experiments 2, 3a, and 3b test predictions from the account.

Experiment 1: Computer-Animated Rolling Wheels

Experiment 1 examined whether the CCI reflects processes specific to mental animation. If it does, there should be no CCI when animated rolling wheels are viewed. If, by contrast, the CCI stems from the processing of rolling motion *per se*, regardless of whether the rolling is perceived or imagined, the CCI should occur even when animated wheels are viewed.

Experiment 1 also examined potential individual differences in susceptibility to the CCI. If the CCI reflects basic perceptual biases, then spatial ability should not affect susceptibility to the illusion. If the CCI reflects limited spatial processing resources, high-spatials may be less prone to the illusion than low-spatials.

Method

Thirty-six subjects viewed white wheel rims (9.3° of visual angle) rolling across a black background. A small dot appeared on the inside of the wheel's rim. The wheels rolled on an untextured white band (7.6° of visual angle) extending the full 38-cm width of the screen. The wheels were displayed on a VAXstation 3100 graphics terminal with a resolution of 1024 x 864 pixels. The system's refresh rate was 60 Hz.

Subjects were told that a dot on a rolling wheel's perimeter should trace a cycloid and were shown a drawing of a cycloid. Subjects were next told that sometimes the wheels' motion was distorted so that the dot did not trace a cycloid. Subjects were told that in these cases they should change the wheel's motion until the dot appeared to trace a cycloid.

The wheel's motion was veridical on one-third of the trials, overrotating on one-third, and overtranslating on one-third. On veridical trials, the wheel's rotational velocity was 0.38 rev/s, and its translational velocity was 5.65 cm (10.7° of visual angle) per second. On overrotating trials, the wheel's translational velocity remained at 5.65 cm/s, but its rotational speed was increased by factors ranging from 1.05 to 1.50. On overtranslating trials, the wheel's rotational velocity remained at 0.38 rev/s, but its translational speed was increased by factors ranging from 1.05 to 1.50.

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 long (14.9° of visual angle). 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". "Spin" and "slide" referred to a relative increase in the wheel's rotation or translation, respectively. Moving the pointer from the point at which the wheel's rolling was veridical toward the "more spin" extreme maintained a translational velocity of 5.65 cm/s, but increased the wheel's rotational velocity. Moving the pointer from the veridical point toward the "more slide" extreme maintained a rotational velocity of 0.38 rev/s, but increased the wheel's translational velocity.

A second mouse button allowed subjects to view the animated result of their ratio adjustment. Subjects could adjust each wheel's ratio and view the resulting rolling display as often as they wished until they believed the dot was tracing the cycloid. A third mouse button initiated subsequent trials. The intertrial interval was about 14 s.

Half the subjects completed the SRT before the computer trials; the remainder completed the test after the computer trials. The test scores of subjects in Experiments 1, 2, 3a, 3b, and three further experiments were pooled and split into tertiles. High-spatials were defined as subjects scoring in the top tertile. Low-spatials were subjects scoring in the bottom tertile.

Results

Eight low-spatials and seventeen high-spatials were included in the analysis. The dependent variable was subjects' *final ratio selections*, the translation/rotation ratio subjects selected at the end of each trial. The translation/rotation ratio of the low-spatials' final selections (mean = 1.21:1) was greater than that of the high-spatials' selections (mean = 0.99:1), $F(2, 72) = 44.21, p < 0.01$ (see Figure 2, next page), implying a greater susceptibility to the CCI among low-spatials. Spatial ability also interacted with the wheel's initial translation/rotation ratio, $F(2, 72) = 29.84, p < 0.01$ (see Figure 2). High-spatials made rolling wheels veridical regardless of the wheel's initial ratio. Low-spatials, though, made overrotating wheels veridical, but selected overtranslating ratios for veridical and overtranslating wheels. On veridical trials, low-spatials chose a mean ratio of 1.13:1.

Discussion

Experiment 1 yielded two conclusions. First, spatial ability mediates susceptibility to the CCI. High-spatials were less prone to the illusion than low-spatials. This suggests that the CCI is not a universal outcome of the way people process rolling motion.

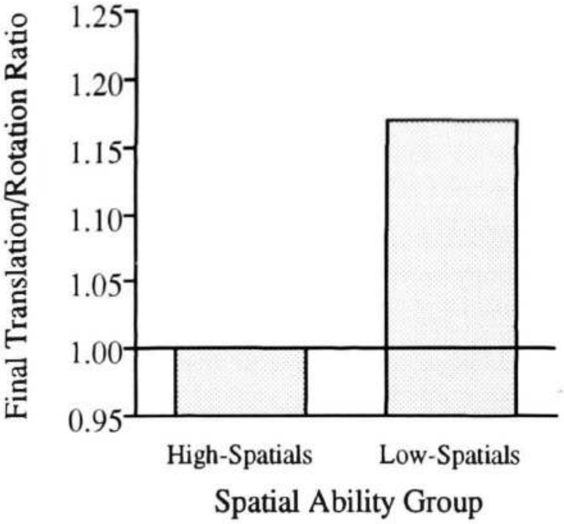

Figure 2: Mean final translation/rotation ratio choice on veridical trials (translation/rotation ratio = 1:1) in Experiment 1 as a function of subjects' spatial ability. The horizontal line indicates the correct response.

Second, animating a wheel does not reduce the susceptibility of low-spatials to the CCI. These subjects chose overtranslating ratios for veridical wheels, implying that they see the dot's path as undertranslating or looped when the wheel's motion is veridical. Because the CCI arises not only when animation is generated mentally, but also when animation is viewed, it likely reflects cognitive rather than perceptual processes.

Experiment 1 also raises the issue of the source of the high-spatials' advantage. Although high-spatials seemed less susceptible to the CCI than did low-spatials, metacognitive or strategic abilities may have allowed high-spatials to simply overcome the CCI and outperform low-spatials. High-spatials may better monitor their susceptibility to the CCI than low-spatials. Allowing subjects to interact with and control a wheel's rolling may permit high-spatials to deploy trajectory correction strategies, thus compensating for the CCI.

To determine whether high-spatials are in fact less prone to the CCI or simply overcome it through metacognitive or strategic processes, we computed d' measures for the Experiment 1 data. Hits were defined as veridical trials on which subjects' final ratios ranged from 0.95:1 to 1.05:1. False alarms were defined as overrotating trials on which the translation/rotation ratio of subjects' final selections was less than 0.90:1. In these instances, subjects did not substantially adjust the motion of overrotating wheels toward the veridical, suggesting that they perceived the dot's curtate cycloid path as the cycloid.

High-spatials more sensitively discriminated cycloid from curtate cycloid trajectories (mean $d' = 0.98$) than did low-spatials (mean $d' = -1.17$), $t(23) = 2.45$, $p < 0.05$. The negative d' value for low-spatials was due to their extremely low hit rates: On veridical trials, they made many misses, perceiving the cycloid as the curtate cycloid and consequently exaggerating the wheel's translation. The d' analysis demonstrates that high-spatials are more sensitive than low-spatials to whether a dot on a rolling wheel's perimeter is tracing the cycloid or the curtate cycloid.

A Processing Account of the CCI

To derive the dot's trajectory accurately, subjects must correctly analyze the rolling wheel's pivoting behavior as the dot approaches, contacts and leaves the surface. When the dot contacts the surface, it is the wheel's *instant center*, the point about which the wheel is rotating at that instant. Subjects may correctly represent the dot's trajectory, particularly its crucial bottom portion, by deriving an instant center corresponding to the dot when it contacts the surface. A rolling wheel's contour, however, contains an infinite number of instant centers as its successive points contact the surface. We argue below that the CCI may stem from the demand on processing resources imposed by the determination of additional instant centers besides the dot.

From the time the dot is at 12 o'clock until the time the dot begins approaching the surface, the dot's behavior is irrelevant to determining whether the dot is tracing the cycloid or the curtate cycloid, which are distinguished by their bottom portions. Because subjects are not trying to derive the bottom portion of the dot's path, they devote few resources to calculating the wheel's instant centers. Processing resources are thus available to derive and update representations of both the wheel's rotation and its translation.

When the dot contacts the surface, subjects must correctly evaluate the wheel's pivoting motion to derive the bottom portion of the dot's trajectory. Subjects thus compute an instant center corresponding to the dot. Although the dot leaves the surface immediately, the processes of computing an instant center, evaluating the wheel's pivoting motion, and elaborating a representation of the dot's trajectory are demanding and noninstantaneous. In addition, the points along the wheel's contour immediately trailing the dot also contact the surface and are thus instant centers. To complete their analysis of the wheel's pivoting behavior and their derivation of the dot's trajectory, subjects may also compute these additional instant centers, even though determining these instant centers does not contribute to the development of an accurate representation of the dot's path.

Computing these additional instant centers may divert resources from the processes that compute and update the rolling wheel's continuous translation. Updating the wheel's translation therefore slows or ceases from the time the dot contacts the surface until the time the dot reaches 7 or 8 o'clock. At this point, subjects may have sufficiently evaluated the wheel's pivoting and adequately represented the dot's path. They stop determining the wheel's instant centers and reattend to the dot at, say, 8 o'clock. Because translation has stopped, subjects' representation of the wheel has essentially rotated in place since the dot contacted the surface, whereas the displayed wheel has rolled to the right. The dot has thus phenomenologically traveled leftward, and if subjects connect the dot's position at 6 o'clock with its position at 8 o'clock in their representation of the dot's path, its trajectory will contain the curtate cycloid's bottom loop.

Experiment 2: Rolling Polygons

The CCI arises because the computation of multiple instant centers imposes so great a processing demand that subjects fail to update their translation representations when the dot contacts and leaves the surface. If a rolling object's instant centers were less closely spaced, subjects would be less likely to compute additional instant centers while attempting to build a representation of the dot's trajectory. More resources would be available to update translation as the dot contacts and leaves the surface, decreasing susceptibility to the CCI.

In Experiment 2, subjects viewed rolling polygons as well as rolling wheels. Whereas a rolling wheel has an infinite number of instant centers, a rolling polygon has only as many instant centers as it has vertices. A rolling triangle has three instant centers and a rolling octagon has eight instant centers. A rolling triangle's three instant centers are more distinct and distantly spaced than a rolling octagon's eight instant centers. Subjects should therefore be more prone to the CCI when viewing rolling octagons than when viewing rolling triangles. More generally, susceptibility to the CCI should increase as the rolling object's number of vertices increases.

Method

The method differed from Experiment 1 as follows: Thirty-one subjects viewed rolling batons, triangles, pentagons, octagons, and circles. Each object was composed of white line segments. A dot appeared next to the rim of each circle or one of the vertices of each object. Each object appeared on six of the experiment's 30 trials. The object's motion was veridical on two of each object's trials, overtranslating on two, and overrotating on two.

Results

Fourteen low-spatials and seven high-spatials were included in the analysis. Subjects made rolling batons and triangles essentially veridical (both means = 1.02:1). Subjects' ratio selections strayed increasingly from the veridical as the number of vertices on an object increased, $F(4, 440) = 9.00$, $p < 0.01$ (see Figure 3). The mean translation/rotation ratios of subjects' selections on pentagon, octagon, and circle trials were 1.06:1, 1.08:1, and 1.14:1, respectively. Susceptibility to the CCI thus increases as the number of vertices on a rolling object increases.

No main effect of spatial ability was observed, and no interaction occurred between spatial ability and the type of rolling object. All subjects performed well on the baton and triangle trials; perhaps each subject viewed too few octagon and circle trials for an effect of spatial ability to show up for these objects.

Discussion

Experiment 2 yielded two main conclusions. First, increasing the number of instant centers by varying the type of object increases susceptibility to the CCI, presumably because processing resources are shifted from translation cumulation as more instant centers are computed. Second, when rolling objects contain few enough instant centers that the competing demand for resources no longer exceeds the capacity of low-spatials, such subjects can perform as well as high-spatials.

Reducing the number of competing instant centers also facilitates the solution of a different physics problem, the yo-yo problem (Anzai & Yokoyama, 1984). In this problem, a yo-yo wound by a string rests on a horizontal surface. Subjects are asked to predict the direction the yo-yo will roll when the string is pulled to the left. The yo-yo will roll to the left because the direction of rotational momentum caused by the tension in the string and the yo-yo's center of rotation at its point of contact with the surface -- its instant center -- is to the left. Subjects' predictive accuracy was about 20% when circular yo-yos were used, but approximately 60% when square and hexagonal yo-yos were used. The increase in accuracy was attributed to the increased saliency of each instant center in the case of the polygonal yo-yos.

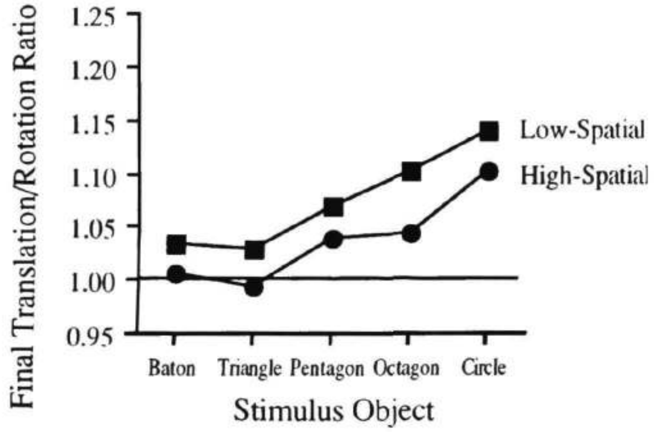

Figure 3: Mean final translation/rotation ratio choice in Experiment 2 as a function of the type of rolling object and subjects' spatial ability. The horizontal line indicates the correct response.

Experiments 3a and 3b: Rolling Wheels with Deleted Portions of Arc

We 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. The portion of the wheel's contour trailing the dot is thus implicated in the CCI because it contains the additional instant centers subjects try to compute. If trailing contour were absent, subjects would be less likely to compute trailing instant centers and would be less prone to the CCI.

Experiment 3a

In Experiment 3a, subjects viewed three types of rolling wheels: wheels in which the 90° of arc trailing the dot were deleted, wheels in which the 90° of arc leading the dot were deleted, and intact wheels. If our account is correct, the CCI should be least apparent for wheels with deleted trailing arc.

Method. The method resembled Experiment 1 except as follows: Twenty-four 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 veridical on five of the trials for each wheel type, overtranslating on three, and overrotating on three.

Results. Eight high-spatial and seven low-spatial subjects were included in the analysis. A main effect of wheel type was found, F(2, 56) = 12.80, p < .01 (see Figure 4). Subjects performed more accurately when trailing arc was deleted (mean = 1.05:1) than when no arc was deleted (mean = 1.15:1), F(1, 56) = 22.88, p < .01 or when leading arc was deleted (mean = 1.13;1), F(1, 56) = 14.59, p < .01. Also, subjects performed no more accurately when leading arc was deleted than on intact wheels. Finally, high-spatials performed more accurately overall than did low-spatials. There was no interaction between wheel type and spatial ability.

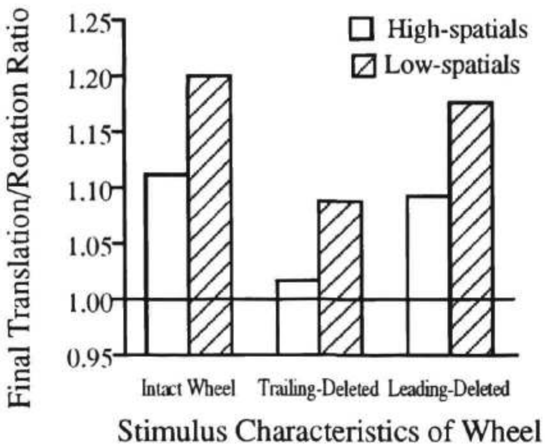

Figure 4: Mean final translation/rotation ratio choice in Experiment 3a as a function of the stimulus type and subjects' spatial ability. The horizontal line indicates the correct response.

Experiment 3b

In Experiment 3a, we deleted 90° of arc to maximize the likelihood that we would eliminate the extraneous instant centers that subjects compute. The instant center account, however, states that subjects stop calculating instant centers when the dot reaches 7 or 8 o'clock. Subjects probably do not continue calculating instant centers until the dot travels as far as 9 o'clock. Given the success of Experiment 3a, we wondered if the instant center account could withstand a more specific test of its predictions. In Experiment 3b, we replicated Experiment 3a using wheels in which we eliminated 45° rather than 90° of arc. If the instant center is correct, subjects should be more accurate when the 45° of arc trailing the dot is eliminated than when no arc is deleted or when the 45° of arc leading the dot is deleted.

Method. The method was identical to that of Experiment 3a except that 45 rather than 90° of arc was deleted either trailing or leading the dot. Fourteen Carnegie Mellon undergraduates participated for course credit.

Results. As in Experiment 3a, a main effect of stimulus type was found, $F(2, 26) = 9.01$, $p < .01$. Subjects were less prone to the CCI when the 45° of arc trailing the dot was deleted (mean = 1.02:1) than when no arc was deleted (mean = 1.10:1), $F(1, 26) = 17.36$, $p < .01$ or when the 45° of arc leading the dot was deleted (mean = 1.08:1), $F(1, 26) = 7.76$, $p < .01$ (see Figure 5). Subjects were as susceptible to the CCI when the 45° of arc leading the dot was deleted as when no arc was deleted, $F(1, 26) = 1.91$, $p > .05$.

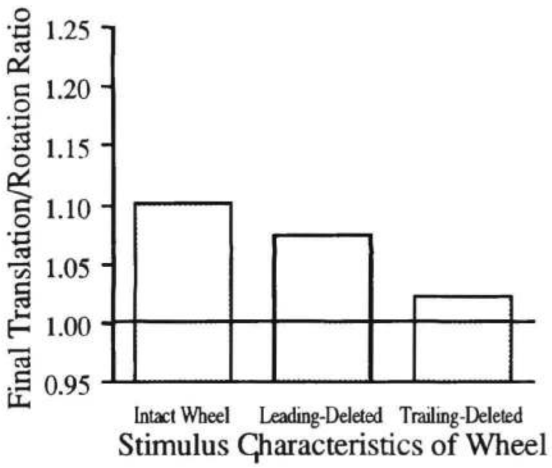

Figure 5: Mean final translation/rotation ratio choice in Experiment 3b as a function of the stimulus type. The horizontal line indicates the correct response.

Discussion

Experiments 3a and 3b yield two conclusions. First, the CCI arises when subjects divert resources from translation cumulation to instant center computation immediately after the dot contacts and leaves the surface. When we reduce the likelihood that these instant centers will be computed, resources are released, allowing subjects to continue cumulating translation and reducing their susceptibility to the CCI.

Second, the cognitive conditions responsible for the CCI are short-lived rather than long-lasting. Subjects appear to compute instant centers 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 about the wheel's center, eliminating 45° of trailing arc should not have reduced susceptibility to the CCI as substantially as it did. That the CCI was virtually eliminated when we deleted 45° of trailing arc suggests that instant center computation is completed by the time the dot reaches 7:30. 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.

General Discussion

Our results have several implications for the basis of the CCI. First, the CCI arises during the cognitive processing of general motion parameters, such as rotation and translation. The CCI does not stem from processes specific to mental animation because animating the wheel did not dispel the illusion. Our results, moreover, cannot be explained by an appeal to peripheral perceptual phenomena, such as eye movements, because the CCI also occurs when the wheel is presented statically (Proffitt et al., 1990). That animation does not dispel the CCI suggests more broadly that simple computer animation may not alleviate information processing errors as kinematic systems become more complex. Kaiser, Proffitt, Whelan, and Hecht (1992) suggest that animation can facilitate the evaluation of complex systems if the animation draws viewers' attention to a single dimension of heuristic utility in understanding the system. We might propose additionally that animation should direct viewers' attention to motion dimensions that are often neglected, such as translation in the case of a rolling wheel.

Second, the CCI may be a reflection of transient resource shortages during the processing of rolling motion rather than a consequence of a universal processing bias. Susceptibility to the CCI was related to scores on a psychometric test of spatial ability. Individual differences in susceptibility to the CCI may thus reflect individual differences in the ability to meet the cognitive demand imposed by the need to process and store visuospatial information simultaneously. These individual differences imply that the CCI is not an inevitable outcome of the way people process rolling motion. A resource approach to understanding kinematic illusions is further supported by the fact that individual differences in cognitive resource availability also predict the ability to integrate relative velocity and relative distance when determining which of two objects will reach its destination first (Law et al., 1993).

Third, the resource shortages leading to the CCI do not persist through the entire course of rolling motion processing, but arise only when a reference point on a rolling object's perimeter contacts and leaves the surface. The CCI was attenuated when we reduced the tendency to derive multiple instant centers by presenting rolling polygons with fewer instant centers. Experiments 3a and 3b showed that instant centers are not computed before the dot contacts the surface. When a point on an object's perimeter contacts and leaves the surface, there is a discontinuity in the point's trajectory. Cognitive resource shortages may be especially likely at discontinuities in a motion, where subjects cannot increment their representation of the motion simply by extrapolating their existing representation of it. They must instead process a boundary between successive segments of motion. Discontinuity processing operations, such as instant center computation, cause subjects to deallocate resources from processing and storing some component of the motion, such as translation, leading to illusions like the CCI.

The processing limitations account suggests why the CCI might arise, explains the CCI's looped form, explains individual differences in susceptibility to the CCI, and accounts for the effects of the nature of the rolling object on the magnitude of the CCI. Our most general point is that the evaluation of kinematic systems depends on particular task demands and the processing resources subjects have available as well as on the nature of the motions themselves.

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