Perception, 1993, volume 22, pages 917–928

Judging rolling wheels: dynamic and kinematic aspects of rotation–translation coupling

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Received 16 July 1992, in revised form 9 June 1993

Abstract. Four experiments were carried out to investigate observers' abilities to judge rolling motions. The experiments were designed to assess whether two important aspects of such motions are appreciated: the kinematic coupling of rotation and translation, and the dynamic effects of gravity. Different motion contexts of rolling wheels were created using computer-generated displays. The first experiment involved wheels rolling down an inclined plane. Observers spontaneously appreciated the anomaly of wheels that failed to accelerate, but they were not able to differentiate between different acceleration functions. Moreover, their judgments were almost exclusively based on the translation component of the rolling motion, neglecting the rotation component. In a second experiment it was found that observers could accurately estimate the perimeter of various objects. Thus, their inability to consider rotation information is not attributable to misperceptions of the geometry of wheels. In a third experiment the finding that rolling wheels appear to overrotate was replicated; however, findings from this experiment also showed, together with those from a fourth experiment, that observers are able to make very accurate judgments about translation–rotation coupling in rolling wheels when information is provided about the orientation of the wheel and the texture of the surface on which it rolls.

1 Introduction

In this study I investigated people's abilities to understand the dynamics of rotary motions of wheel-like objects. Wheel motions have two components, the forward motion of the center of the wheel (translation) and the rotation of the wheel around its axle (rotation). To accurately judge a rolling wheel the coupling of these two components has to be understood. In this paper I present evidence that, although observers are in principle sensitive to this information, they fail to make accurate judgments when the stimulus display is diminished or when the relevant information does not become salient.

A theory suggested by Proffitt and Gilden (1989) might explain this finding. They distinguish two aspects of motion: first, particle motions which are easily understood by human observers, and second, extended-body motions, which are harder to understand. In the case of a rolling wheel its translation is a particle motion. That is, the common motion of the wheel is fully described by the translation of its center. Particle motions are not orientation-specific. The rotation of the wheel, on the other hand, has to be described in terms of a relative or extended-body motion, which is orientation-specific. This holds, of course, only for wheels with orientation clearly marked through coloring or discernible spokes. Proffitt and Gilden (1989) proposed that difficulties in making visual judgments of dynamic events such as rolling motions occur as soon as a motion cannot be described as a particle motion but involves extended-body motions. They further suggest that observers base their judgments of a dynamic extended-body event on one salient aspect of the motion. That is, in the case of a rolling wheel judgments would be based on particle motions while extended-body transformations are ignored. Taken literally, the theory makes the implausible prediction that observers neglect the rotation of the wheel altogether. The present study was designed to test the following more moderate claim. With increasing complexity of the dynamic situation, observers should become less sensitive to translation–rotation coupling, focusing on the translation of the wheel (particle motion) while neglecting the rotation of the wheel (extended-body motion). Complexity here consists of introducing gravity into the rolling context.

Rolling motions typically occur in two different contexts depending on whether or not a constant force acts on the wheel. A wheel rolling down an inclined plane would be an example of a case in which gravity constantly accelerates the wheel. Proffitt et al (1990) found that people's explicit understanding of this situation is very poor. Even though subjects knew that the wheels would accelerate down the ramp, they could only guess how mass, radius, and mass distribution of the wheel would influence its acceleration. Almost none of them appreciated that only mass distribution has a bearing on the acceleration of the wheel; the more the mass is distributed towards the center of the wheel, the faster it accelerates. Even experienced physics teachers tended not to take this fact into consideration when asked to make quick judgments predicting which of several different wheels on a ramp would accelerate at the fastest rate.

In this study I assessed whether observers are sensitive to the visual extended-body information provided by a rolling wheel. In experiment 1 I tested spontaneous visual judgments and thus tried to tap implicit knowledge about translation–rotation coupling. There is evidence that the kinematic information that is necessary to make accurate judgments about such events might be particularly easy to extract from stimuli presented in a graphic-animation context (Kaiser et al 1992). Thus, wheels rolling down a ramp were presented in animation to obtain spontaneous judgments about their motions.

Interestingly, the results of research that has been done with accelerated particles (Bloch and Bonnet 1966; Bozzi 1959; Gottsdanker et al 1961; Runeson 1974) suggest that observers might not even be able to make accurate judgments about the particle aspects of such motions. For example, the perception of similar events that involve gravity have thus far only been investigated for particle motions (Bozzi 1959; Runeson 1976). Bozzi found that a point particle sliding down an incline at constant acceleration rates appeared to speed up too much towards the end of its motion. Stimuli were perceived to look most natural when they accelerated for the first third of the trajectory and then continued their descent at constant speed. However, this result should not surprise us, since such behavior is in keeping with many natural events when air resistance (drag) or friction will, at some point, stop further acceleration. Constant acceleration only occurs for a frictionless mass in a vacuum. Similarly, Runeson (1974) showed that uniform linear particle motions are not perceived as such, even in motion contexts where gravity is not relevant. Particles appeared to speed up at the beginning and to slow down towards the end of the motion sequence.

The results obtained in experiment 1 suggest that, in extended-body-motion contexts, observers are not spontaneously sensitive to the coupling of the translation and rotation of a wheel. However, they are able to make qualitative judgments as to whether the wheel should accelerate at all. This lack of spontaneous appreciation, though, does not imply that observers cannot attend to the underlying kinematic information. Thus, in experiments 2, 3, and 4, observers' attention was drawn to the kinematic information given by rolling motions. The results of experiment 2 established that observers are able to extract the static information that specifies the amount of texture that a wheel covers per revolution. They made fairly accurate judgments about the circumference of wheels and other objects.

In experiments 3 and 4 I investigated people's abilities to judge translation–rotation coupling for rolling motions in which no unbalanced forces act on the wheel, that is a wheel rolling on a level surface. Results in experiment 3 demonstrate that observers are able to extract the kinematic and geometric information that is involved in rolling motions. The results put the findings obtained by Vicario and Bressan (1990) in a more general context and suggest that clear perceptual information about the orientation of the wheel and the texture of the background are necessary conditions for the attentive extraction of kinematic information about rotation–translation coupling.

2 Experiment 1: wheels on a ramp

The purpose in this experiment was to investigate the ability of observers to appreciate the motions of events in which translation and rotation interact. Wheels rolling down an inclined plane are suitable for an analysis of these factors, since angular and linear velocities of the wheel may be perceived as independent or as correlated factors. In this motion context, gravity is the only external force that is required to produce the motions. Experiment 1 was designed to test if perceptual biases exist when wheels are chosen instead of point particles. It was hypothesized that spontaneous judgments would be biased for wheels that are rolling down a ramp. The motion context including gravity should make the event difficult to judge. In this experiment I also assessed whether irregularities of rotation and translation are equally detectable and whether they interact, for example in the sense that a lack of linear acceleration might be compensated by faster angular acceleration.

Bozzi (1959) and Runeson (1974) used dynamically unnatural events in their studies. Their objects started from rest, that is, during the transition from rest to motion they had to accelerate instantaneously, which is physically impossible. This anomaly might in fact have been a determining factor of their results. There is some evidence, however, that the transition from rest to motion is not the only source for misperception of velocity. Runeson (1976) found biases to persist when the initial start of the object was occluded. To avoid this problem, all objects used in experiment 1 were already in motion when they appeared on the screen. Also, the average velocity was kept constant to avoid acceleration being correlated with average velocity.

2.1 *Method*

2.1.1 *Subjects.* A total of 24 University of Virginia undergraduates, 12 females and 12 males, participated in order to partially fulfill a research option in an introductory psychology class.

2.1.2 *Stimuli.* The following sequences of wheels moving down a ramp were first created on a Sun 3/60 Color Graphics Workstation and then recorded frame-by-frame onto 0.75 in videotape with the aid of a RGB Videolink 1400 encoder. The wheels had two differently colored halves to make their orientation easily noticeable. Three translational motions (constant, quadratic acceleration, and acceleration to the 4th power) and three corresponding rotational motions were used. The displacement along the ramp was determined as follows. For a given point in time t, the displacement from the top of the ramp was $x_t = x_0 + v_0 * t + a * t^{exp}$ (x_0 and v_0 were the position and velocity, respectively, at the beginning of the event, a was a constant reflecting the slope of the plane, *exp* the exponent of 1, 2, or 4). Rotation was determined correspondingly. Note that in the canonical case, rotation and translation accelerated quadratically ($exp = 2$).

The translational and rotational motions were paired combinatorially into 9 unique events. Two different slopes of the ramp were introduced, yielding a total of 18 stimuli. The average velocity of the wheel was kept constant for all trials of identical slope. Thus, observers could not base their answers on the duration of an event, which would have predicted the translational acceleration if all wheels had started with the same velocity.

2.1.3 *Procedure.* The stimuli were presented on a Mitsubishi VS495R projection monitor with a 91 cm × 69 cm screen. At a viewing distance of 4 m the display of the ramp covered the whole width of the screen, which subtended a visual angle of 13 deg. The wheel was already in motion when it appeared on the screen. The wheel diameter subtended approximately 1.5 deg. The trajectory of the wheel was orthogonal to the observer's line of sight as it moved from left to right down the ramp.

For economic reasons subjects were tested in groups of 2 observers. They were asked to judge wheels that they could think of as car tires rolling down a steep road. In a dimly lit room, each stimulus was presented twice with an intervening pause of 3 s. Then, observers were asked to judge the motion—specifically how natural it appeared to them—by circling a number on an individual sheet of paper. To anchor the naturalness scale, 9 practice stimuli were shown which covered the whole range of different translation–rotation combinations. Then, three blocks of 18 stimuli each were presented. Each block had a different random order of stimuli and the order of blocks varied between subjects. The first block was considered practice and the results from this block were thus not included in the analysis.

The naturalness ratings (on a scale from 1 to 6) allowed subjects to convey their impression of the event. Subjects were told that gravity, but no other unseen forces, would act on the wheel. If the event clearly looked impossible or unnatural under these conditions, they should give it a rating of 1, if it clearly looked natural it should receive the rating 6. After the practice, observers were told that they had seen the whole range of stimuli. They were encouraged to use the whole scale if they had not already done so.

2.2 *Results*

Subjects identified events that translated at constant rates as unnatural regardless of their rotational motion. Moreover, translations that accelerated more than is possible did not strike observers as particularly unnatural.

A repeated-measures ANOVA revealed a large main effect for translation ($F_{2,44} = 67.68$, $p < 0.0001$) and a smaller one for rotation ($F_{2,44} = 24.73$, $p < 0.001$). Wheels that were translating down the ramp at a constant speed were singled out as unnatural, whether or not the rotational component of the motion was canonical. This can be seen in figure 1a. Figure 1b depicts the same data with one line for each level of rotation. Wheels translating at a constant speed received lower naturalness ratings than did wheels with canonical translation ($F_{1,23} = 134.93$, $p < 0.0001$) or 4th-power translation ($F_{1,23} = 141.30$, $p < 0.0001$). The naturalness ratings for the latter two did not significantly differ from one another. The interaction between translation and rotation was also significant ($F_{4,88} = 6.1$, $p < 0.0002$).

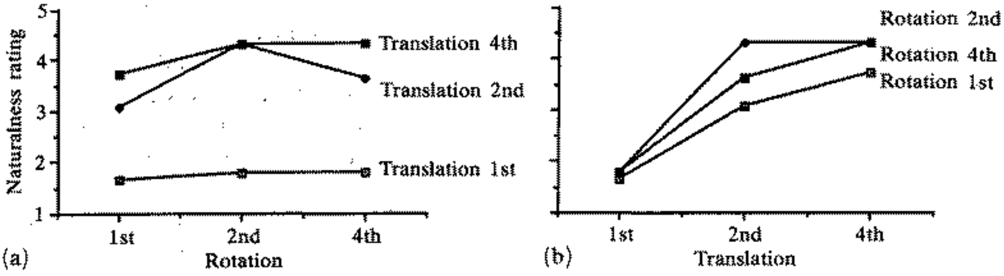

Figure 1. Mean naturalness ratings obtained in experiment 1, ranging from 1 (least natural or impossible) to 6 (most natural). In (a), one line is plotted for each translation function of the wheel (1st = constant speed, 2nd = quadratic acceleration, 4th = 4th-power exponential acceleration). The same data are shown in (b), but in this case, one line is plotted for each rotation function.

Slope of the ramp had no effect on observed naturalness. No gender or order effects were found. That is, subjects did not change the way they used the naturalness scale over the course of the experiment. Trials that had canonical translation with overrotation did not differ from trials that had canonical rotation and overtranslation ($F_{1,23} = 2.69$, $p > 0.10$). However, trials with constant rotation but canonical translation looked more natural than did those with canonical rotation but constant translation ($F_{1,23} = 8.39$, $p < 0.01$). Thus, observers were far more sensitive to anomalous translation than they were to anomalous rotation.

2.3 *Discussion*

Observers' impressions of what a natural rolling event should look like were guided primarily by the translational motion component. Animated events tended to look natural as long as the center of the wheel accelerated, regardless of the exponent of acceleration and regardless of the rotational component. In particular, constant translational motions looked bizarre whereas constant angular velocities did not. That is, observers have a mainly qualitative understanding of the effect of gravity. They appreciate that gravity accelerates the wheel, but they are insensitive to a wide range of its quantitative effects. This finding suggests that Clement's (1982) contention that people cannot determine whether a given motion is caused by gravity or not, may just hold for qualitatively similar motions.

Also, observers were not able to make accurate spontaneous judgments of rotation – translation coupling. They seemed to consider rotation only in such cases where translation was natural. There are two possible interpretations for this result. First, observers may not be able to extract and integrate the kinematic information that is necessary to judge the coupling of rotation and translation. In experiment 2 I investigated this alternative. Second, the situation may have been too complex to make efficient use of the kinematic information, but if attended to, information about rotation and translation might be accessible. This hypothesis was tested in experiments 3 and 4.

3 Experiment 2: perceived circumference

If observers are not able to spontaneously appreciate the coupling of rotation and translation, it could be because they are not able to make accurate judgments of the circumference of the wheel with respect to its translational displacement. This inability might be explained by the following hypothesis. The lack of definable edges on the contour of the wheel may prevent observers from detecting orientation differences of the wheel which would make an accurate judgment of the rotation impossible. This hypothesis might be able to explain the results obtained by Vicario and Bressan (1990), who found an illusion that reflects an inability to judge rotation – translation coupling even when observers directly attend to this coupling.

They used an interactive task that required subjects to adjust the translational speed of a wheel while looking at it. The wheel consisted of fairly dense radial lines (spokes). The surface on which the wheel rolled was either absent or a plain line. In every cycle, the wheel would appear at one side of the monitor, roll across it, and disappear. By pressing a key, observers could change the translational speed of the wheel for the next cycle. Observers were instructed to do so until the translational speed would be adequate for the rate of rotation of the wheel, given that it rolled smoothly on a level surface. Between trials, the size of the wheel, the rate of rotation, and the presence of a surface were manipulated. The results showed that, for a given rotation, the amount of translation was overestimated by up to 80% for very small wheels.

There are a number of reasons why it is doubtful whether the results obtained by Vicario and Bressan (1990) generalize to everyday situations that provide richer information about the orientation of the wheel and the texture of the background. First, the authors might have studied a problem that consists of keeping track of the orientation of the wheel. The wheel consisted of 30 identical spokes. This fact would partially explain their finding that the effect was attenuated for larger wheels, the spokes of which were easier to follow. An additional problem is posed by the rotational velocities that were chosen. They were all very slow (between 3.5 and 14.1 rev min^{-1}, whereas 100 – 200 rev min^{-1} would be typical for a car driving at 30 km h^{-1}), and one could expect the illusion to disappear with fast rotations, especially since the illusion was largest for the slowest speed that was tested.

Third, the fact that observers overestimated the translation that would result from a given rotational speed, could be due to an overestimation of the circumference of the wheels. The perimeter of circular objects might be especially hard to judge because they do not have edges that might be joined together by a simple mental operation. The perimeter of a square, for example, could be estimated by judging the length of one side and adding it on to itself four times. To test this hypothesis, in experiment 2 I sought to assess observers' ability to judge the perimeter of differently shaped objects and the mapping of this perimeter into translational displacement.

3.1 *Method*

3.1.1 *Subjects.*

A total of 400 University of Virginia undergraduates participated in a mass-testing session in order to partially fulfill a research option in an introductory psychology class. Some 30 subjects failed to complete the task described in the procedure section and data from them were thus not included in the analysis. None of the subjects had participated in experiment 1.

3.1.2 *Stimuli.*

Each subject (between-subjects design) was presented with one of six objects (circle, triangle, square, rectangle, ellipse with the two centres aligned vertically or horizontally) on a sheet of paper. The objects were identical in perimeter. Each stimulus consisted of a drawing of one object that rested on a surface, the orientation of the object was indicated by a cross at its bottom. A circle was seen by 55 subjects, a triangle by 63, a square by 57, a rectangle by 64, a vertical ellipse by 64, and a horizontal ellipse by 67 subjects.

3.1.3 *Procedure.*

The task description was a between-subjects factor. One task was to mark the paper where the cross on the contour of the object would end up after exactly one revolution along the horizontal surface (indicated by a straight line). A second set of instructions was given to another group of subjects and asked them to estimate the perimeter of the object by marking its length on the paper. In this condition, the drawings of the stimuli remained unchanged. The first task description was given to 181 and the second to 189 subjects.

3.2 *Results and discussion*

No difference was found between the two sets of instructions. The distances (or perimeters) for circles were judged significantly smaller than they actually were ($t_{55} = 4.07$, $p < 0.0002$); mean perimeter estimations were 15.3% too short for circles. Judgments for all other shapes did not differ significantly from the objective values. Since this effect of underestimating the circumference of a circle is small, and opposite to Vicario and Bressan's finding that translation is overestimated for rolling wheels, it is safe to conclude that geometrical properties of balls/wheels cannot explain observers' erroneous perceptions of rolling motion.

4 Experiment 3: rolling wheels

Experiment 3 was conducted to examine whether observers would be able to extract kinematic information about rotation–translation coupling in rolling wheels. In particular, it was designed to assess whether explicit attention to this coupling, and visual cues about the orientation of the wheel and the surface on which it was rolling, would improve observers' judgments. For isolated rotational motion components, some data have been collected by Gibson and Cooper (1988). They found that observers were slightly biased in their judgments of extrapolating the rotation of a projected wire-frame cube around its centroid. Subjects saw the cube in motion, then the display disappeared and the task was to indicate how far it would have rotated after a certain time interval if it had continued its motion. Subjects underestimated the required rotation. This finding is compatible with Vicario and Bressan's (1990) observation that the amount of translation is overestimated for a given rotation. In both studies, however, stimulus displays were used that provided fairly diminished cues about orientation of the object and texture of the background. Thus, these data do not allow the conclusion that observers are generally unable to appreciate the coupling of rotation and translation.

In order to demonstrate, in more general terms, whether observers are sensitive to the kinematics of rolling motion, Vicario and Bressan's experiment was modified and replicated. In one condition, a perceptually salient surface, on which the wheel rolled, was introduced. The task was a purely perceptual one, that is, observers did not have to adjust translational speed, but they were asked to watch the display and to rate if, and by how much, the wheel would overrotate or underrotate.

Vicario and Bressan (1990) used an interactive task that required subjects to adjust the translational speed of the wheel while looking at it. This task might have directed most attention to manipulating the wheel. Thus, quantitative conclusions about perceptual errors when judging the coupling of rotation and translation might be problematic, especially since it has been demonstrated that objects appear to move slower when they are being explicitly tracked (Bloch and Bonnet 1966). Asking observers for judgments of whether the wheel was rotating too much or too little minimized this problem.

4.1 *Method*

4.1.1 *Subjects.* Students enrolled at Ludwig-Maximilians-Universität, München (10 females and 10 males) were paid for their participation.

4.1.2 *Stimuli.* Computer-generated wheel-like objects were used. In one condition wheels with 30 spokes were used: these looked exactly like the ones used by Vicario and Bressan (1990). That is, the wheel appeared on the dark-grey screen without any further reference cues. A second condition introduced a structured checkerboard-like surface (background) in front of which the wheel rolled, as is depicted in figure 2.

A Compaq 486 DX2-66 computer with a TIGA-MDB11 graphics card and a 15 in EIZO monitor (resolution 1024 × 768) was used for all stimulus displays. The following 4 canonical events were generated: a large wheel (6 cm diameter) and a small wheel (3 cm diameter) each rolling at 5 and 10 rev min^{-1}. These parameters correspond to those used by Vicario and Bressan (1990). By changing translational velocities for each of these events 6 additional stimuli were created: 3 that rotated too much (1.33, 1.66, and 2.0 times the canonical rate) and 3 that rotated too little (0.83, 0.66, and 0.5 times the canonical rate) resulting in 28 rotation/translation pairings, including the 4 canonical events. In all noncanonical cases the wheel would slip (overrotation) or slide (underrotation). Each pairing was presented in random order, once with background (block 1) and once without background (block 2). The order of these two blocks was counterbalanced.

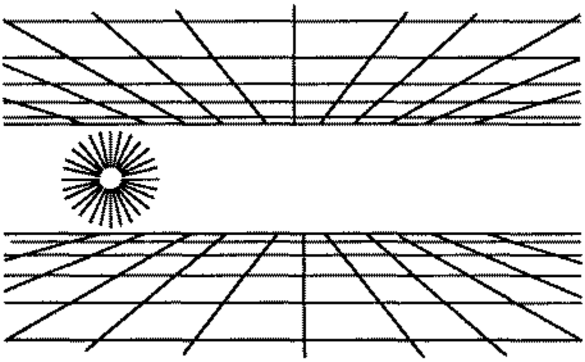

Figure 2. The display used in the textured-background condition of experiment 3. The wheel moved from left to right and rotated clockwise.

4.1.3 *Procedure.* Observers were tested individually in a dimly lit room. The trajectory of the wheel was orthogonal to the observer's line of sight as the wheel moved from left to right; the wheel was already in motion when it entered the screen. Viewing distance was approximately 50 cm. Seven practice trials were given (no background) to familiarize observers with the task and to anchor the rating scale. With its motion started by the observer clicking a button on the mouse, a wheel rolled across the screen once. Then subjects could either choose to watch the same event again or make a judgment using a 13-point rating scale. The center (0) of the scale signified perfect rolling; underrotation or overrotation could be indicated by choosing negative or positive numbers between −6 (extreme underrotation) and +6 (extreme overrotation). A short break was taken between the two blocks.

4.2 *Results*

For stimuli that lacked background, observers produced the same bias found by Vicario and Bressan (1990), ie they had a tendency to perceive a canonical wheel to overrotate or slip. However, with the textured background this illusion disappeared.

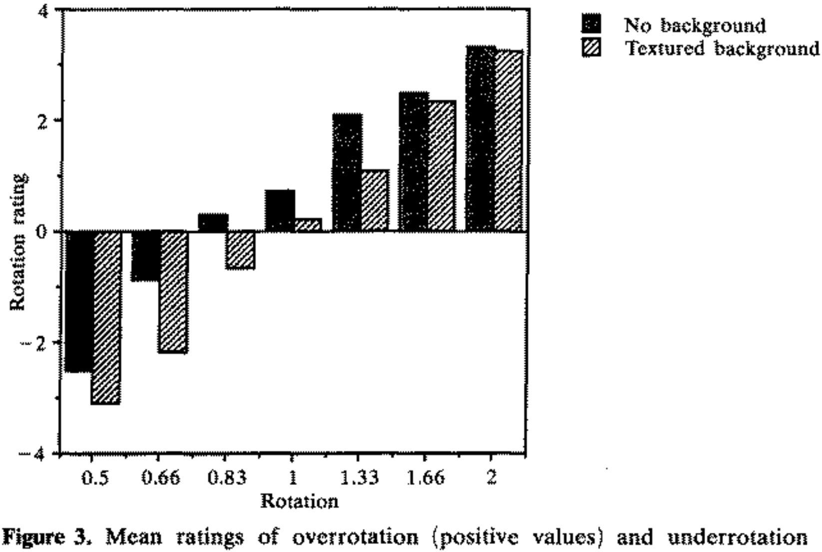

Figure 3. Mean ratings of overrotation (positive values) and underrotation (negative values) obtained in experiment 3. Rotation values on the abscissa are the ratio of rotation:translation. Values below 1 represent underrotation (sliding), values above 1 represent overrotation (slipping). A value of 1 represents smooth rolling.

A repeated-measures ANOVA revealed a strong effect of background ($F_{1,114} = 29.36$, $p < 0.0001$). Main effects were also found for diameter ($F_{1,114} = 26.1$, $p < 0.0001$) and translational velocity ($F_{1,114} = 50.3$, $p < 0.0001$). The illusion was stronger for small wheels (average ratings of +0.7 versus +0.2) and it was stronger for wheels that translated faster (ratings of +0.8 versus +0.1). Gender and order of presentation did not reach significance, neither did any of the interaction terms.

As shown in figure 3, wheels that actually were overrotating received even higher overrotation scores when the background was absent. Likewise, actually underrotating wheels received smaller negative ratings when the background was absent. That is, for trials with background texture the whole distribution of ratings seems shifted toward overrotation compared with no-background trials. For canonical wheels (rotation = 1), figure 3 reveals that they were judged to overrotate ($t_{78} = 3.06$, $p < 0.003$) when the background was absent. However, with the background present, judgments were not significantly different from 0.

4.3 *Discussion*

The illusion reported by Vicario and Bressan (1990) was replicated for comparable displays. Their finding that observers overestimate the translation of a wheel that has a given rotational velocity is in perfect agreement with the present finding that observers overestimate the rotation of a smoothly rolling wheel. The effect is strongest for small wheels. However, the manipulation of introducing a textured background makes the illusion disappear. Thus, the illusion seems to arise when information about the texture of the background is insufficient.

5 Experiment 4: faster wheels in a richer environment

In experiment 4 I assessed whether observers would also be able to make accurate judgments of translation–rotation coupling in cases where the wheel rolled at faster velocities, such as those which would be typical for bicycle or car wheels.

5.1 *Method*

5.1.1 *Subjects.* University of Virginia undergraduates, 8 females and 8 males, participated in order to partially fulfill a research option in an introductory psychology class. They had not participated in the previous experiments.

5.1.2 *Stimuli.* Computer-generated wheel-like objects were used. The wheels were made to look solid by the addition of a shaded area representing the rim. Different parts of the rim would become visible as the wheel rolled past the stationary observer. The wheel had two differently colored halves to make its orientation easily detectable. The surface on which it rolled was structured to make its relation to the wheel as clear as possible. A texture gradient was suggested by a tiled-floor pattern and provided an anchor for judging how far the wheel had come relative to its circumference. This pattern consisted of a digitized image of a brick floor. The image of the floor was videotaped and then digitized with an image-capture board that allowed a resolution of 512 × 512 with 16 bits per pixel. The background of the scene consisted of a wall and a University building behind it, an image which provided further reference points for distance information. The rotating wheel was then superimposed on this realistic background.

The following 3 canonical events were generated on a Sun 3/60 Color Graphics Workstation and recorded frame-by-frame onto videotape using the same equipment as in experiment 1: wheels rolled across the scene in 1, 2, and 3 s; during that time the wheel made two complete revolutions. The resulting rates of rotation were in the range of that of a wheel rolled across a level surface [ie at 40, 60, and 120 rev min^{-1}

(Griffing 1987) compared with a range from 3.5–14.1 rev min^{-1} used by Vicario and Bressan (1990)]. For each of these events, 6 additional stimuli were created, 3 that rotated too much (1.25, 1.5, and 2.0 times the canonical rate) and 3 that rotated too little (0.8, 0.66, and 0.5 times the canonical rate) resulting in 21 rotation/translation pairings, including the 3 canonical events. For example, one event had the translational speed that corresponded to a wheel rolling at 40 rev min^{-1} combined with the rotational speed of 80 rev min^{-1}. In all such noncanonical cases the wheel would slip (overrotation) or slide (underrotation).

5.1.3 *Procedure* The viewing conditions were identical to those of experiment 1. The wheel was already in motion when it appeared on the screen. The diameter of the wheel subtended approximately 2 deg. The trajectory of the wheel as it moved from left to right was orthogonal to the observer's line of sight. Thus, the rim was visible on the right side of the wheel at the beginning of the wheel's motion. The rim disappeared when the wheel was in the center of the screen and then reappeared on the left side of the wheel.

Subjects were tested in groups of 2 observers in a dark room. All trials were presented three times in different randomly ordered blocks. The first block was considered practice and the data from it were thus not included in the analysis. Each stimulus was presented twice with a pause of 3 s in between. During practice, subjects had as much time as they wanted to make a decision as to whether the wheel was rotating too fast or too slow for smooth rolling. Subjects wrote down a rating about the naturalness of the motion, which could range from 1 (least natural) to 6 (most natural). Subjects were asked to treat a smooth rolling event as most natural.

5.2 *Results*

Overall, observers were able to detect whether the stimulus represented a rolling event or not. The canonical events were judged to be most natural. As is visible in figure 4, naturalness ratings were distributed symmetrically around the canonical rolling events. That is, the more the wheel was sliding (rotation <1) or slipping (rotation >1), the less natural the event was judged. In about 75% of the cases observers were able to tell if the wheel rotated too much or too little. A repeated-measures ANOVA revealed that rotation was significant ($F_{6,84} = 38.28$, $p < 0.0001$). All naturalness judgments for adjacent rates of rotation differed significantly from one

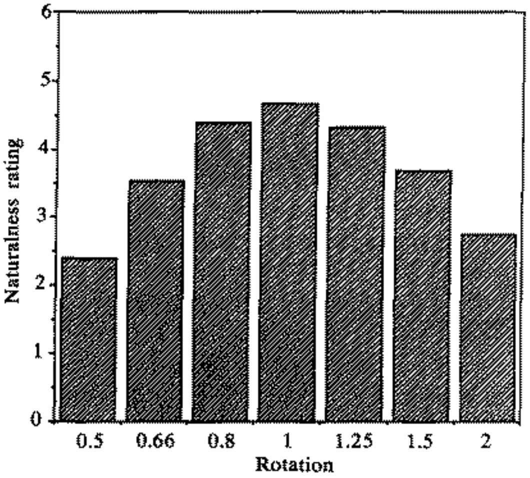

Figure 4. Mean naturalness ratings obtained in experiment 4. The scale ranged from 1 (least natural) to 6 (most natural).

another (range from $F_{1,14} = 5.42$, $p < 0.036$ to $F_{1,14} = 46.37$, $p < 0.0001$). However, events with underrotation were judged to be as natural as the comparable event with overrotation. For example, a wheel rotating at half the rate of smooth rolling was not judged differently from a wheel rotating at twice that rate.

Significant effects were also found for the speed at which the center of the wheel translated ($F_{2,28} = 4.54$, $p < 0.02$). Slow speeds looked slightly less natural than did fast or intermediate speeds ($F_{1,14} = 5.73$, $p < 0.03$). No significant effects for gender were found.

5.3 *Discussion*

Observers are able to make accurate judgments about rotation-translation coupling even if they have to judge wheels moving at very fast velocities. Changing the appearance of the wheel and the background did not seem to influence the results. Observers' ability to extract kinematic information of rolling wheels is degraded somewhat for faster rotational and translational velocities. However, reliable rotation-translation coupling judgments can still be made if rich cues about wheel orientation and background texture are provided.

6 General discussion

In the motion context of a wheel rolling down a ramp, observers are neither spontaneously sensitive to the acceleration function induced by gravity nor do they appreciate the rotation-translation coupling in this situation. Rather, the qualitative distinction between a wheel translating at constant speed versus one that accelerates seems to guide their impression of naturalness. This finding is in agreement with contentions that judgments about dynamic events are primarily based on the particle-motion aspect of the system (Proffitt and Gilden 1989).

However, when given sufficient information, observers are able to make correct judgments about the coupling of rotation and translation as long as gravity does not complicate the situation (a wheel rolling across a level surface). Only in the absence of texture do observers fail to appreciate translation-rotation coupling. Thus, the illusion that rolling wheels appear to overrotate has been shown to be task-dependent. The effect described by Vicario and Bressan (1990) only appears when no information is provided about the surface the wheel is rolling on. This is compatible with findings suggesting that relative components of wheel motions are more easily detectable than are common components (Cutting and Proffitt 1982; Wallach 1976). When two point lights on the rim of an invisible wheel were presented, observers noticed the rotation (relative motion) more easily than they did the translation of the center of the wheel (common motion). That is, in the absence of reference cues, the visual system is more sensitive to the relative-motion component of rotation. It has yet to be investigated whether observers integrate common-motion and relative-motion components or whether they judge the motion holistically.

Acknowledgements. I thank Marco Bertamini, Linda Bunker, Frank Durgin, Jackie Johnson, Mary Kaiser, Dennis Proffitt, and Art Schulman for valuable advice at various stages of the project. Two anonymous reviewers provided very thoughtful comments on an earlier version of this paper. Steve Jacquot and Bernd Sewald provided programming assistance; Steve DeGroot, Gerhard Kramer, Rob Marino, Gail Morris, and Isa Schinzel helped conducting the experiments.

References

Bloch H, Bonnet C, 1966 "La perception du movement: Examen de quelques problèmes" *Année Psychologique* **66** 231-262

Bozzi P, 1959 "Le condizioni del movimento "naturale" lungo i piani inclinati" *Rivista di Psicologia* **53** 337-352

Clement J, 1982 "Student's preconceptions in introductory mechanics" *American Journal of Physics* **50** 66-71

Cutting J E, Proffitt D R, 1982 "The minimum principle and the perception of absolute, common, and relative motions" *Cognitive Psychology* **14** 211 – 246

Gibson B S, Cooper L A, 1988 "Perceiving and extrapolating continuous spatial transformations" paper presented at the 29th Annual Meeting of the Psychonomic Society, Chicago, IL, November 10 – 12

Griffing D F, 1987 *The Dynamics of Sports: Why that's the Way the Ball Bounces* (Oxford, OH: Dalog)

Gottsdanker R, Frick J W, Lockard R B, 1961 "Identifying the acceleration of visual targets" *British Journal of Psychology* **52** 31 – 42

Kaiser M K, Proffitt D R, Whelan S, Hecht H, 1992 "The influence of animation on dynamical judgments: Informing all of the people some of the time" *Journal of Experimental Psychology: Human Perception and Performance* **18** 669 – 690

Proffitt D R, Gilden D L, 1989 "Understanding natural dynamics" *Journal of Experimental Psychology: Human Perception and Performance* **15** 384 – 393

Proffitt D R, Kaiser M K, Whelan S M, 1990 "Understanding wheel dynamics" *Cognitive Psychology* **22** 342 – 373

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

Runeson S, 1976 *The Perceptual Concept of Velocity tested with Strong Frame of Reference, Observer-Determined Start, and Partly Occluded Track* Report number 187 (Sweden: University of Uppsala, Department of Psychology)

Vicario G B, Bressan P, 1990 "Wheels: a new illusion in the perception of rolling objects" *Perception* **19** 57 – 61

Wallach H, 1976 *On Perception* (New York: Quadrangle)