Learning to perceive the relative mass of colliding balls: The effects of ratio scaling and feedback

DAVID M. JACOBS and CLAIRE F. MICHAELS
Vrije Universiteit, Amsterdam, The Netherlands

and

SVERKER RUNESON
Uppsala University, Uppsala, Sweden

The theory of direct perception holds that competent observers are able to detect optical patterns that specify the relative mass of colliding balls. Heuristic theorists, on the other hand, claim that judgments of relative mass are based on variables that do not specify relative mass. We contrasted these views with an experiment in which participants were given feedback on their ratio-scaled estimates of the relative mass of simulated colliding balls. Correlations between judged relative mass and various kinetic and kinematic measures of the collisions revealed that (1) judgments of relative mass become more accurate with feedback, (2) different observers use different variables, (3) during training, many observers change which variables they use, (4) before training, observers tend to use nonspecifying variables or combinations thereof, (5) after a minimal amount of training, at least some observers seem to detect mass-specifying information, and (6) the judgments do not support a generalization of the heuristic model of Gilden and Proffitt (1989, 1994). These findings suggest that direct perception of relative mass is a skill that can be developed through appropriate training.

Kinematics is the branch of mechanics that is concerned with aspects of pure motion, such as position, velocity, and acceleration. Kinetics (or dynamics), in contrast, is the branch of mechanics that deals with motion by taking into account such variables as force, mass, and friction. Because kinetic properties of the environment are important for the guidance of action, it would be beneficial for animals to perceive them visually, and indeed, humans, for instance, have been shown to perceive kinetic properties (e.g., Michotte, 1963; Runeson & Frykholm, 1983). The fact that the optical array consists only of kinematic variables creates a problem: How are kinematic variables exploited in the perception of kinetic properties?

The nature of this exploitation has been debated by proponents of the theory of direct perception (Runeson, 1995; Runeson, Juslin, & Olsson, in press; Runeson & Vedeler,

1993) and proponents of the theory of heuristics use (Gilden & Proffitt, 1989, 1994; Proffitt & Gilden, 1989; Todd & Warren, 1982). The theory of direct perception assumes that kinetic properties of the environment are specified by kinematic patterns. Smart perceptual mechanisms (Runeson, 1977) are hypothesized for the detection of these specifying patterns, and thus, ecologically relevant dynamic properties are said to be perceived directly. Heuristics theorists, although they sometimes acknowledge that specifying information exists, hold that nonspecifying kinematic variables are used for the visual perception of kinetic properties; such cues are enriched by the application of heuristics.

The primary testing ground of these competing theories has been the perception of the relative mass of colliding balls.¹ Variables that specify relative mass have been pitted against nonspecifying variables as predictors of judgments of relative mass. A brief review of the physics of collisions permits us to describe the relevant variables (see also Runeson, 1995). The imaginary line that connects the centers of colliding balls at the moment of impact is called the collision axis. Colliding balls exchange momentum only along this collision axis. The collision component of a ball's velocity is the projection of the velocity on the collision axis. Collision components are changed as a result of a collision. No momentum is exchanged along the orthogonal, sweep axis; the sweep component of the velocity of a colliding ball is unchanged by a collision. Figure 1 presents a two-dimensional collision and identifies

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Figure 1. A two-dimensional collision, with the kinematic variables exit speed ($|v|$), scatter angle (α), and precollision speed ($|u|$) and an invariant specifying the mass ratio (m_a/m_b).

several kinematic variables that might be used for the judgment of relative mass.

Exit speed and scatter angle have figured importantly in heuristics accounts of relative mass perception. The exit speed of a ball is its speed after the moment of impact—in the case of Figure 1, the lengths of v_a and v_b .² The scatter angle of a ball is the angle between the direction of its movement before and after impact—for the left ball in Figure 1, α_a . The heuristic model presented by Gilden and Proffitt (1989, 1994) holds that people use these two variables and associated heuristics for the perception of relative mass. For the speed heuristic, the ball with the greater exit speed is taken to be the lighter, and for the angle heuristic, the ball with the greater scatter angle is taken to be the lighter. If these heuristics are in conflict, the more salient will be applied. Each heuristic is either salient or nonsalient. The speed heuristic is salient only if the exit speed of the faster ball is at least twice that of the slower ball. The angle heuristic is salient if one of the balls has a scatter angle greater than 90° . The model does not provide estimates of mass if the heuristics conflict and both are salient or both are nonsalient. Note that the heuristics theory allows only one variable to be used on any trial.

The correlations between the mass ratio of colliding balls and the above-mentioned kinematic variables depend on the particular set of collisions used in an experiment. In contrast, independent of the set of collisions, mass ratio correlates perfectly with the relative amount of velocity change (Runeson, 1995).³ Proponents of the direct approach claim that competent observers may be able to detect such mass-specifying information.

Gilden and Proffitt (1989) found support for their heuristic model from two experiments. In their Experi-

ment 1, participants almost always identified the heavier ball as heavier if it collided with a stationary lighter ball. In contrast, performance was poorer if the lighter ball collided with a stationary heavier ball. These findings were explained with the heuristic model: Identification was accurate if both heuristics correctly implied that the incoming ball was the heavier and was less accurate if the heuristics conflicted and salience rules did not favor the correct one. Gilden and Proffitt (1989) argued that their results ran counter to the theory of direct perception, because the mass ratios of the colliding balls were always specified by kinematic patterns, but were not so detected.

In Experiment 2 of Gilden and Proffitt (1989), participants reported which ball was heavier, but in addition, they rated the dissimilarity of the masses. Again, performance, as measured by the percentage of correct judgments, was less accurate if the heuristics were both salient but conflicted. Furthermore, in these conflicting situations, the distribution of the dissimilarity judgments exhibited a bimodal tendency. In Gilden and Proffitt's (1989) interpretation, observers applied different heuristics, but the judged dissimilarities were always large, because the cue values were large in order to be salient. Again, Gilden and Proffitt (1989) argued that these effects run counter to the assumption that observers directly detect mass-specifying information.

However, according to Runeson and Vedeler (1993), the results of Gilden and Proffitt (1989) did not distinguish between the direct and the heuristic explanations, because crucial parameters were held constant. First, one of the balls was always stationary before impact. Second, the angle of the incoming ball, relative to the collision axis, varied only between observers; for each single observer, it was constant throughout the experiment. In this particular situation, mass ratio was related one to one not only to the relative amount of velocity change, but also, for instance, to the scatter angle of the incoming ball. Hence, one cannot determine on which of these variables individual observers relied. To determine which variables are used in the perception of relative mass and, hence, to distinguish between the competing theories, a set of collisions that does not confound relevant variables is needed.

The variables under consideration can be unconfounded by using appropriate variations in the precollision velocities of the colliding balls (Runeson & Vedeler, 1993). Runeson and Vedeler carried out three experiments in which collisions were simulated with an increasing variety in precollision velocities. In Experiment 1, one ball was initially stationary, and the angle of the incoming ball was constant relative to the collision axis, as in the experiments by Gilden and Proffitt (1989). In Experiment 2, the balls had different initial velocity components on the collision axis, but they still had equal velocity components on the sweep axis. In Experiment 3, the balls had different initial velocity components on both the collision and the sweep axes; all the variables under consideration were thereby unconfounded. The authors concluded that observers relied on a specifying invariant, because the binary

mass discriminations were more closely associated with the simulated mass ratios than with any of the considered nonspecifying kinematic variables or linear combinations thereof.

Note, however, that the heuristic model holds that observers use different variables for different collisions, depending on salience. Gilden and Proffitt (1994) reanalyzed the results of Experiments 1 and 2 of Runeson and Vedeler (1993), who had analyzed their data over all the collisions presented in each experiment. Gilden and Proffitt (1994) claimed that the results of these first two experiments can be explained with the heuristic model, but they did not reanalyze the results of Experiment 3. In a later article, Runeson (1995) showed that the heuristic model cannot account for the results of this third experiment; rather, they can be explained only by the participants' exploitation of information that specified mass ratio. Because the candidate kinematic variables were successfully unconfounded only in Experiment 3 of Runeson and Vedeler, this third experiment is the most relevant experiment with colliding balls for a comparison between the direct and heuristics theories.

However, the appropriate variety of precollision velocities is not the only aspect that sets Experiment 3 of Runeson and Vedeler (1993) apart from other experiments with colliding balls. All the observers in the experiment, which included the two authors, had experience with the task in at least one earlier experiment, suggesting the possible importance of perceptual learning. Michaels and de Vries (1998) systematically examined the issue of learning to perceive a kinetic property—peak force exerted by stick-figure pullers. Participants made ratio judgments of peak force and were trained with feedback; their performance improved dramatically. Regression analyses were used to determine which kinematic variables were used. The results showed, among other things, that observers differed in the variables they used and that observers changed in which variables they used. It was concluded that novice observers might rely on simple, nonspecifying variables and that, with appropriate practice and feedback, they might discover better variables and thereby perform as experts. Relatedly, Runeson et al. (in press) found significant improvements of performance and a transition from cues to information usage in the colliding balls paradigm after observers were given feedback.

These findings suggest that feedback might affect observers' use of variables for the perception of relative mass; direct perception of relative mass might be a skill that is possessed by expert observers, but not by novices. The purpose of the present study, then, is twofold. First, we want to further examine the importance of learning with feedback for the perception of relative mass and, thereby, for the debate between heuristics theory and direct perception theory. Second, we ask whether the findings of Michaels and de Vries (1998) can be generalized and extended to the paradigm of colliding balls. As in that

study, participants are asked to make quantitative judgments, which might reveal the exploited kinematic variables with more precision than the binary mass discriminations typically used in the colliding balls paradigm, wherein participants are only asked to judge which ball is heavier.

The heuristic model presented by Gilden and Proffitt (1989, 1994) predicts binary discriminations of which ball is heavier. We assembled what we think is a fair ratio version of their model, because we wanted to test whether people use heuristics for judgments on a ratio scale. The original model was modified on two points. First, in our version, the heuristics have continuous salience functions, instead of binary ones. For example, the range of scatter angle differences from 0° to 180° corresponds to a range of saliences of the angle heuristic. More precisely, we used the standardized scores of the differences in exit speed and scatter angle as the salience of the associated heuristic. Gilden and Proffitt (1989, 1994) themselves suggested the possibility of continuous salience functions, which have the advantage that the heuristics will not have the same salience as often as they do when they have only two levels of salience. Second, in our version, the speed heuristic takes the standardized difference in exit speed as the basis for judgments of mass ratio, and similarly, the angle heuristic takes the standardized difference in scatter angle as the basis for judgments of mass ratio. As in the original model, observers are assumed to apply the more salient heuristic.

Note that this ratio version is based on the same principles as the binary version of the heuristic model. Like the binary version, it claims that observers are not sensitive to mass-specifying information and base their judgments either on the exit speeds or on the scatter angles, depending on salience. As a result, the predictions of the two versions are very similar. We have already mentioned that the binary version does not provide mass estimates if the heuristics conflict and have the same salience. This is the case in 8 of the 68 different collisions used in the present experiment. The two versions of the model take the same ball to be the heavier in all but one of the other 60 collisions. In sum, the main differences between the two versions are that the ratio version predicts quantitative estimates of mass, in addition to binary predictions, and that the ratio version makes predictions for all collisions. These differences allow us to test the model with quantitative judgments of relative mass.

In addition to the heuristic model and the direct detection of mass-specifying information, we consider the possibilities that observers' judgments are based on the difference in exit speed alone, on the difference in scatter angle alone, or on a linear combination of these differences. The correlations among all these candidate kinematic variables for the to-be-used collection of collisions are presented in Table 1. The correlations with a specifying invariant (i.e., the simulated mass ratios) can be interpreted as maximum levels of performance: The judg-

Table 1
Correlations Among the Kinematic Variables, in the Pretest and the Posttest

Variable	1	2	3	4	5
1. Specifying invariant*	—	.56	.88	.84	.93
2. Exit speed difference		—	.32	.71	.60
3. Scatter angle difference			—	.82	.95
4. Heuristic model				—	.93
5. Exit speed difference + $.08 \times$ scatter angle difference.†					—

*Correlates perfectly with the simulated mass ratios. †We used the linear combination of the differences in exit speed (m/sec) and scatter angle (rad) that best predicts the simulated mass ratios to calculate the correlations in this table.

ments of mass of an observer who relies only on the difference in exit speed, for instance, cannot correlate more highly than .56 with the simulated mass ratios.

We hypothesized, on the basis of the results of Michaels and de Vries (1998), that novice observers might use variables that correlate only moderately with the simulated mass ratios. Assuming that the use of such nonspecifying variables would yield less satisfying feedback than the use of specifying information, perceivers might change in the variables they use during training. Finally, given enough feedback, perceivers might discover a specifying invariant. Confirmation of these expectations would further support people's ability to use mass-specifying information and would generalize the findings of Michaels and de Vries to the colliding balls paradigm.

METHOD

Participants

Eight students at the University of Uppsala were paid for their participation.

Apparatus

The collisions were simulated and displayed by means of a one-of-a-kind analog computer simulation system (Runeson & Vedeler, 1993). A digital computer controlled the experimental variables and sequenced the phases of trials and sessions: setup, collision display, response recording, feedback, pauses, and so forth. The collisions were displayed on a monitor oscilloscope with green high-intensity phosphor and were projected onto a ground glass screen. A black mask with a round 140-mm-diameter opening (17.7° of visual angle) covered the screen. After a smooth initial acceleration (Runeson, 1975), two 13.5-mm-diameter (1.7° of visual angle) circles took about 1.5 sec to reach the point of impact at the center of this display. As in Runeson and Vedeler, we simulated collisions with a restitution factor of 0.9, which represents about the highest elasticity of real-world collisions. The vertically oriented screen was viewed through a large collimator lens system that allowed free head movements without changing the angular properties of the display. Another mask with a rectangular opening (200 mm wide, 100 mm high) was placed on the observer's side of the collimator in order to restrict viewing to the better portions of the lens. An alphanumeric display directly below the circular collision display window could show two rows of 20 characters and was used as a response monitor for the observers.

Design

The experiment consisted of a 64-trial pretest without feedback, a 288-trial training with feedback, and a 64-trial posttest without feedback. In the pretest and posttest, eight mass ratios were simulated; they differed by equal logarithmic steps from 1:8 to 8:1. In the

training blocks, nine mass ratios were simulated; they differed by equal logarithmic steps from 1:10 to 10:1. The training consisted of four blocks of 72 trials.

The factorial combination of two pairs of collision components and two pairs of sweep components formed four pairs of precollision velocities. The collision components of the precollision velocities were 38 mm/sec (4.8° /sec) and 13 mm/sec (1.6° /sec) in opposite directions or 64 mm/sec (8.1° /sec) and 13 mm/sec (1.6° /sec) in the same direction. The sweep components of the velocities of the balls with the higher and lower collision component were, respectively, 38 mm/sec (4.8° /sec) and 15 mm/sec (1.8° /sec), or 15 mm/sec (1.8° /sec) and 38 mm/sec (4.8° /sec), always in opposite directions.

Figure 2 presents the collisions that followed from these initial velocity conditions and the mass ratios that were simulated in the pretest and the posttest, and Table 1 presents the resulting correlations between the candidate kinematic variables and the mass ratios. In training, these correlations were slightly higher, because the range of the simulated mass ratios was slightly wider.

The two balls were distinguished by their outlines; one was dotted, and the other continuous. The different outlines were randomly assigned to the heavier and the lighter ball. The display was mirror reversed and rotated in steps of 30° , also randomly. Thus, despite the replications (four times in the test phases and eight times in the training), the chance that observers would recognize collisions was minimal.

Procedure

The experiment was divided into two sessions, carried out on consecutive days. The first session included the instructions, the pretest, and two training blocks. The second session included the remaining two training blocks, the posttest, and a debriefing conversation. The instruction phase consisted of the participant's reading of written instructions and eight trials without feedback. Mandatory pauses of at least 5 min, with refreshment offered, were included after the pretest and after each block of training—that is, after about every 25 min. Furthermore, optional pauses were suggested every sixth trial. Each session lasted about $1\frac{1}{2}$ to 2 h.

The participants started a series of six trials by pushing a button. After two consecutive and identical presentations of a collision, the participant entered his or her estimate of the mass ratio by turning a knob. Turning the knob moved a marker along the upper row of the alphanumeric display. The dialed ratio also appeared as a numerical ratio (e.g., 1:2.3) in the middle of the bottom row of this display. Forty-one answer alternatives could be chosen; they varied by equal logarithmic steps from 1:20 to 20:1. A ratio of 1:15 indicated, for example, that the ball with the continuous outline was perceived as 15 times heavier, and a ratio of 2:1 indicated that the ball with the dotted outline was perceived as twice as heavy. A chosen ratio was confirmed by pushing a ready button; on test trials, this also initiated a new trial.

On the training trials, the confirmation of a judgment led to visual and auditory feedback. A marker appeared above the point of the answer scale closest to the simulated mass ratio. The simulated

Figure 2. Superimposed diagrams of the collisions used in the pretest and posttest. Each of the four pairs of precollision velocities results in eight different collisions, labeled +4 through -4, with the mass ratio (m_a/m_b) differing by equal logarithmic steps from 1:8 to 8:1, where m_a refers to the mass of the dotted circle and m_b to the mass of the continuous circle.

ratio was also shown numerically in the middle of the digital display. Auditory feedback indicated whether a judgment was correct, acceptable, or wrong. A low beep followed by two higher beeps indicated that a judged ratio was correct; it differed from the simulated ratio by less than three steps on the logarithmic response scale, where the stepsize was 0.15 natural log units. A high beep alone indicated that the judgment was acceptable; it differed less than six steps from the simulated ratio. A low beep alone indicated that the judgment was wrong; it differed more than six steps from the simulated ratio. The participants were paid according to their performance. In the pretest, training, and posttest, correct judgments were rewarded with 1.5 SEK (about US\$ 0.18), and acceptable judgments with 0.75 SEK. Wrong judgments were not rewarded.

RESULTS

In order to detect the expected differences between and within individuals, the data were analyzed observer by observer and block by block. We first addressed observers' abilities to perceive relative mass, followed by analyses whose aim was to reveal the kinematic variables on which the mass judgments were based. Figure 3 presents (the logarithms of) the judgments, averaged per simulated mass ratio, in the pretest and in the posttest for each participant. All the averaged judgments reasonably approximate the simulated mass ratios, which suggests that the participants were able, at least to some extent, to perceive the relative mass of colliding balls.

Note that Figure 3 does not show a constant error; on the average, a 1:1 ratio would have been perceived as such. Neither did we expect a constant error, because, in contrast to earlier studies, we analyzed and plotted the mass of the ball with the dotted outline divided by the mass of the ball with continuous outline and the outlines were assigned randomly to the balls. We chose to use the dotted versus continuous distinction precisely because the outlines were assigned randomly. This allowed us to assess performance and to determine the kinematic variables on which observers relied with Pearson product-moment correlations, despite their insensitivity to the constant errors that might have been expected if different distinctions had been used.⁴

We calculated correlations that involved the simulated or judged mass ratios, using the logarithms of these ratios, because the logarithms form a symmetrical scale around the 1:1 ratio. The correlations between the judgments and the simulated mass ratios, for each block of trials of each participant, are presented as a part of Figure 4. They ranged from $r = .50$ to $r = .97$. All of them differed significantly from zero ($p < .01$); variations in the judged mass ratios went along with variations in the simulated mass ratios. The judgments correlated more highly with the mass ratios in the posttest than in the pretest. A t test for paired samples indicated that this difference was significant [$t(7) = 2.2$, $p = .03$].⁵ Indeed, the participants

Figure 3. Averaged logarithms of judged mass ratios as a function of the logarithms of the simulated mass ratios, in the pretest (left panel) and posttest (right panel) for each participant. The simulated mass of the dotted circle is referred to as m_a and the simulated mass of the continuous circle as m_b .

were able to perceive relative mass, and their perception of mass improved after practice with feedback.

Of course, high correlations between the simulated mass ratios and the judgments do not constitute evidence that the observers detected mass-specifying information. To conclude that a kinematic variable is used for the judgments of mass, its correlation with the judgments should be significantly higher than the other candidate kinematic variables. We calculated, for each block of trials of each observer, the correlations between the judgments and (1) a specifying invariant (i.e., the simulated mass ratios), (2) the difference in exit speed, (3) the difference in scatter angle, and (4) the predictions of the heuristic model;⁶ and again per block of trials, the multiple correlations of the judgments regressed against both the differences in exit speed and those in scatter angle. The critical question, then, is how these correlations compare. They are presented in Figure 4, which also indicates the blocks in which the highest correlation differed significantly from the second highest and third highest correlations, according to a t test for two independent correlations (Bruning & Kintz, 1987).

In the first block, the judgments of Observers 2 and 4 correlated most highly with the difference in exit speed (open triangles) and with a linear combination of the differences in exit speed and scatter angle (open diamonds). The linear combination was not a significantly better predictor than the difference in exit speed, which means that only the difference in exit speed was used in the first block by these observers. Recall that the difference in exit speed correlated only moderately ($r = .56$) with the simulated mass ratios and, hence, could not lead to accurate judgments of mass. Perhaps because of the discouraging

feedback, these 2 observers changed strategies and came to rely on a combination of the differences in exit speed and in scatter angle in the later blocks, which led to reasonably accurate judgments. In the final blocks, Observer 2 continued to rely on a combination of the differences in exit speed and scatter angle. The nominal correlations, although not the significances, hint that Observer 4 continued to explore the available kinematic variables and discovered mass-specifying information (filled dots) in the last two blocks.

The other observers seemed to rely on specifying information or on a linear combination of the differences in exit speed and scatter angle from the start. In most of the blocks, the correlations between the judgments and mass-specifying information and the linear combination did not differ significantly. Nevertheless, the nominal correlations and the blocks in which the differences were significant, as is shown in Figure 4, suggested three trends. First, Observers 1 and 5 seemed to rely on the combination throughout the experiment. Second, Observers 6, 7, and 8 seemed to start with reliance on the combination and later come to detect specifying information. Third, Observer 3 seemed to detect specifying information in all the blocks. Finally, we note that the correlations between the judgments and the predictions of the heuristic model (filled triangles) are almost never the highest. This suggests that the observers did not perceive according to the heuristic model.

As was mentioned before, not all of the differences shown in Figure 4 were significant. For instance, the judgments of Observer 1, who seemed to rely on the combination throughout the experiment, correlated significantly higher with the combination than with a specifying invariant only in two of the six blocks (Blocks 2 and

Figure 4. Pearson product-moment correlations between the judgments and a specifying invariant (INV), exit speed difference (ESD), scatter angle difference (SAD), the multiple correlations between the judgments and both the exit speed and the scatter angle differences (ESA), and the predictions of the heuristic model (HM), in the pretest (Block 1), training (Blocks 2, 3, 4, and 5), and the posttest (Block 6). In blocks marked with an A, the highest correlation was significantly different from the second highest correlation at a .05 level, and in blocks marked with a B, the highest correlation was significantly different from the third highest correlation.

6). Similarly, the judgments of Observer 3, who seemed to detect specifying information throughout the experiment, correlated significantly higher with a specifying invariant than with the combination only in two blocks (3 and 6). However, analyzed over all six blocks, these differences were both highly significant ($p < .001$).

Furthermore, in many single blocks, the differences were significant. For instance, in the first block, the judgments of Observers 2 and 4 correlated significantly ($p <$

.01 and $p < .001$, respectively) higher with the difference in exit speed than with a specifying invariant. In the last two blocks, in contrast, their judgments correlated significantly ($p < .05$ for Observer 2 and $p < .001$ for Observer 4) higher with a specifying invariant than with the difference in exit speed. In sum, the conclusions that observers differ in the variables they use, change in the variables they use, and converge on the more useful variables seem to be reliable.

DISCUSSION

The participants in the present experiment practiced with feedback to make quantitative judgments of the relative mass of colliding balls. We investigated the importance of perceptual learning for the debate between heuristics theory and direct perception theory and, in addition, sought to generalize the learning process that has recently been demonstrated in the visual perception of force (Michaels & de Vries, 1998). We found that (1) the observers' judgments became more accurate after feedback; (2) different observers used different variables; (3) there was a change in which variables the observers used; (4) before training, the observers tended to use non-specifying variables or combinations thereof; (5) after a minimal amount of training, at least some perceivers seemed to detect mass-specifying information; and (6) the observers did not perceive according to our generalization of the heuristic model of Gilden and Proffitt (1989, 1994).

Results 1 to 5 generalize the findings of Michaels and de Vries (1998). This suggests that the process of perceptual learning that they demonstrated is not an artifact of the paradigm of force perception. In both paradigms, novice perceivers sometimes begin by exploiting kinematic variables that are correlated only marginally with the to-be-perceived kinetic property, which seems to be in accordance with the theory of heuristics use. However, Michaels and de Vries argued that the use of lesser correlated, more highly correlated, or specifying kinematic variables—as indicators of task demands and levels of expertise—also fits with the direct perception approach. What still separates the approaches is that heuristic models claim that observers are limited to the use of non-specifying variables.

As is stated by Result 6, the observers' judgments did not support our generalization of the heuristic model of Gilden and Proffitt (1989, 1994). However, different extensions of the model are possible. For instance, the salience of the heuristics could be weighted differently, which would model a tendency to apply one heuristic more often than the other, or one could somehow include individual differences. We cannot rule out the possibility that the present results might be explained by using another heuristic model. In our view, this reflects a general weakness in the theory of heuristics use—namely, that it is always possible to contrive a model that postdicts the observed results and, hence, that it is impossible to falsify the approach with performance characteristics. A similar critique has been levied against the direct approach; it can seek other kinematic patterns that, although they are not specific to the properties to be perceived, explain the observed performance. This complicates attempts to distinguish the direct and the heuristic approaches (Hecht, 1996). Likewise, the direct perception approach might seem difficult to distinguish from other, more cognitive theories. To take the extreme, the results of the present experiment cannot be used to contrast the claim that ob-

servers detect mass-specifying information from the claim that observers independently detect the four relevant velocities and use these to compute estimates of relative mass. Why, then, should one maintain the different theories?

In the first place, as is demonstrated in the present study, specific models that are motivated by the different theories are often distinguishable with performance characteristics. Furthermore, predictions about performance characteristics are not the only differences between direct and cognitive approaches. Recently, Runeson et al. (in press) used participants' estimations of confidence in their judgments to distinguish between the competing theories. A common finding in cognitive tasks is that participants are *overconfident* or *well calibrated*—they tend to believe that their judgments are more accurate than they really are, or they correctly estimate the accuracy of their judgments. In contrast, in sensory discrimination tasks, observers tend to be *underconfident*—their performance exceeds their confidence.

Runeson et al. (in press) used this different disposition toward confidence between sensory and cognitive tasks as an index of whether (and when) the relative mass of colliding balls is perceived directly or inferred through heuristics. They reasoned that the inferential nature of heuristic processing would be revealed by overconfidence, whereas direct perception would be evidenced by underconfidence. The participants in their experiment were trained with feedback. Before training, the majority of them was overconfident or well calibrated, as in cognitive tasks. After training, the majority of them was underconfident, as in sensory tasks. This suggested that novices and experts perform mass discriminations in different modes. Runeson et al. concluded that, before training, the discrimination of relative mass is an inferential task. After training, in contrast, relative mass discrimination is a perceptual task—that is, participants seem to detect mass-specifying information directly.

This conclusion takes us back to Result 5: After a limited amount of training, some observers appear to detect mass-specifying information, which seems to be in agreement with the findings of Runeson et al. (in press). Nevertheless, some other observers came to rely on a linear combination of the differences in exit speed and scatter angle, and for the remaining observers, it was not clear whether they came to rely on specifying information or on a combination. The difficulty of distinguishing between these kinematic variables might be due to the high correlation between them (for the optimal linear combination, $r = .93$; see Table 1). With such a high correlation, one could even argue that the combination should be considered as information specifying relative mass.

It is important to note, however, that the one-to-one relation between information specifying relative mass and the mass ratios is guaranteed by boundary conditions that can be assumed to hold over a wide range of situations (Runeson, 1983). In contrast, the high correlation between the mass ratios and the combination is more or

less coincidental; different precollision kinematics will lead to different correlations. Given the results of the present study, observers might be expected to converge on other variables than the combination if they are trained with sets of collisions in which the combination correlates poorly with the simulated mass ratios. This possible influence of the particular set of collisions encountered in training is addressed elsewhere (Jacobs, Runeson, & Michaels, 2000).

We conclude here by reiterating the analogy between the demonstrated process of perceptual learning and Bernstein's idea of motor learning, as has been suggested by Michaels and Beek (1995), Michaels and de Vries (1998) and Runeson et al. (in press). Many variables in the ambient optic array correlate with to-be-perceived kinetic properties; some variables specify them. A novice observer may not have discovered a specifying invariant. When the plethora of optical variables is confronted, one is picked up and used to guide perception. This appeared to be the difference in exit speed for some observers in our experiment. Other optical variables, such as the difference in scatter angle, are then ignored, somewhat like the redundant degrees of freedom frozen out in motor learning (Bernstein, 1967). With training, observers become attentive to more useful variables; in our experiment, they came to rely on, at least, a combination of the differences in exit speed and scatter angle. Finally, a smart perceptual device (Runeson, 1977) might master the many optical variables by detecting a specifying invariant, like an expert in coordination who harnesses the many degrees of freedom into a coordinative structure (Turvey, 1990).

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NOTES

1. In the present experiment and the other colliding balls experiments discussed here, participants are shown frictionless collisions of circles presented on a two-dimensional screen.
2. Note that we use velocity in the sense of a vector with both a length and a direction. Speed, on the other hand, is used as a scalar—namely, as the length of a velocity vector.
3. This holds regardless of the elasticity of a collision (Runeson, 1983). However, the specifying kinematic patterns will be more complicated if, for instance, friction and spin are considered.
4. Traditionally, the *motor object* (the ball with the greater precollision velocity component on the collision axis) versus *target object* (the ball with the smaller precollision velocity component on the collision axis) distinction has been used to analyze (binary) judgments of mass. Such analyses revealed that observers overestimate the mass of the motor object; the point of subjective equality offset varied between 21% and 54% (see Runeson, 1995).
5. Our quantitative mass judgments also revealed a motor object bias; a simulated 1:1 ratio (motor object over target object) showed average perceived ratios of 2.2:1 in the pretest and 1.5:1 in the posttest. This indicates that the judgments of at least some participants were based on nonspecifying variables that correlated with the motor versus target object distinction. However, the bias is not very useful as a measure of which kinematic variables observers use, because the distinction correlates significantly with several kinematic variables. The value, then, of defining mass ratio as dotted/continuous instead of motor object/target object is that the variance normally associated with the motor object bias can be tracked down to individual kinematic variables.
6. All tests on correlations were done on the Z transformations of the correlations, $Z_r = \frac{1}{2}[\ln(1+r) - \ln(1-r)]$.
7. The predictions of the heuristic model were calculated separately for the practice blocks and the test blocks, because of the different sets of collisions that were used.

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