In Physics Education, Perception Matters

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ABSTRACT— Student difficulties in science learning are frequently attributed to misconceptions about scientific concepts. We argue that domain-general perceptual processes may also influence students' ability to learn and demonstrate mastery of difficult science concepts. Using the concept of center of gravity (CoG), we show how student difficulty in applying CoG to an object such as a baseball bat can be accounted for, at least in part, by general principles of perception (i.e., not exclusively physics-based) that make perceiving the CoG of some objects more difficult than others. In particular, it is perceptually difficult to locate the CoG of objects with asymmetric-extended properties. The basic perceptual features of objects must be taken into account when assessing students' classroom performance and developing effective science, technology, engineering, and mathematics (STEM) teaching methods.

High school and college students often encounter difficulties grasping and applying concepts in introductory physics classes. Physics educators and researchers have responded to this challenge with the development of the field of physics education research (PER; McDermott, 1991). Within PER, students' difficulties are frequently attributed to misconceptions about physics concepts and addressed through teaching methods including tutorials (McDermott, Shaffer, & the Physics Education Group at the University of Washington, 2002) and interactive lecture demonstrations (Sokoloff & Thornton, 2004) designed to explain difficult physics concepts in new or varied ways. Rarely, however, are basic and domain-general (i.e., not exclusively physics-based) mechanisms of perception thought about as a hindrance to physics learning. The field of cognitive science (including psychology and neuroscience) has identified several general principles of perception. Could domain-general perceptual processes also influence physics learning? If so, this would suggest rethinking certain physics teaching methods to include consideration not only of physics concepts but also of basic learning strategies allowing for more accurate perceptual understanding.

Here, we use the concept of center of gravity (CoG), often referred to as center of mass,[1] to explore the role of basic perceptual features in student understanding. Several classroom studies involving CoG have been published (Brose & Kautz, 2011; Liby, Friedenberg, & Yancopoulos, 2009; Ortiz, Heron, & Shaffer, 2005). We focus on research by Ortiz et al. (2005), who used college physics and engineering classroom data to show that student performance on CoG questions and related topics involving extended objects (e.g., a balanced baseball bat) with an unequal or "asymmetric" mass distribution was much poorer than on similar questions involving discrete-asymmetric objects (e.g., two nonidentical crates on opposite sides of a seesaw). Originally interpreted as evidence that students have an incomplete understanding of CoG, it is also possible that there is something inherently different in the perception of discrete objects versus extended objects that contributes to poorer performance on the latter. That is, differences in students' performance on the CoG problems mentioned above may—at least in part—be due to general perceptual features that make it harder to determine the CoG of some objects relative to others. In support of this idea, Redish (2004) suggested that students may perceive an extended baseball bat differently than the discrete crates and ignore their new, formal physics knowledge about CoG. In other words, difficulties solving the baseball bat CoG problems (and similar asymmetric, extended objects akin to the baseball bat) may be driven by general perceptual features of items, not simply subpar physics knowledge.

Previous research has shown that individuals' ability to locate CoG changes based upon the perceptual features of objects. For instance, symmetry plays a large role in the ability to accurately locate CoG. For extended shapes, such as triangles, rectangles, and polygons (Davi, Doyle, & Proffitt, 1992), it is perceptually easier to determine the CoG of

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symmetric relative to asymmetric objects. For discrete systems of multiple dots, greater reflective and rotational symmetry results in increased accuracy in locating the system's CoG (Liby & Friedenberg, 2010). Orientation and size of objects also impact the difficulty of locating an object's CoG for extended shapes (Bingham & Muchisky, 1993), as do size ratio, separation, and orientation of systems of discrete dots (Friedenberg & Liby, 2002, 2008). The Ortiz et al. (2005) findings described above for the baseball bat and crates suggest that the extension of an object or system (i.e., whether it is discrete or extended) may also contribute to students' ability to accurately locate the CoG of an object.

In the current work, participants were recruited to take part in a CoG finding task outside of a physics classroom. By providing participants with a simple definition of CoG, and by varying the perceptual features contained by objects on the CoG finding task, we effectively removed our CoG finding task from a physics context to explore how and if general perceptual features impact CoG finding. We crossed the perceptual features of symmetry (i.e., symmetric vs. asymmetric) and extension (extended vs. discrete) in our CoG finding task (see Figure 1). We hypothesize that problems requiring determination of the CoG for an object that is both asymmetric and extended may be most perceptually demanding for students because solutions require simultaneously taking into account two perceptual features (i.e., symmetry and extension). Our goal was to demonstrate how basic perceptual features of objects might explain poor performance observed when students work on CoG questions and related topics in the physics classroom.

While our CoG finding task was intentionally performed outside of a physics context, we did gather information on the extent of our participants' previous physics exposure (i.e., number of physics classes taken in college). This information allowed us to explore if participants' previous physics education related to performance on the CoG finding task. By controlling for participants' physics experience, we provide additional evidence that it is the perceptual features manipulated within the experiment (rather than conceptual physics knowledge per se) that are responsible for our results.

METHODS

Participants

Participants drawn from a Midwestern university community ($N = 51$; 24 males) ranged from 18 to 32 years of age ($M = 21.3$ years, $SD = 3.5$). Although we did not specifically recruit participants to represent varying levels of physics experience, participants varied greatly in experience with physics: 30 participants had taken no college level physics classes, 17 had taken 1–3 physics classes (most likely as part or all of an introductory physics sequence), and 4 participants had taken 4 physics classes.

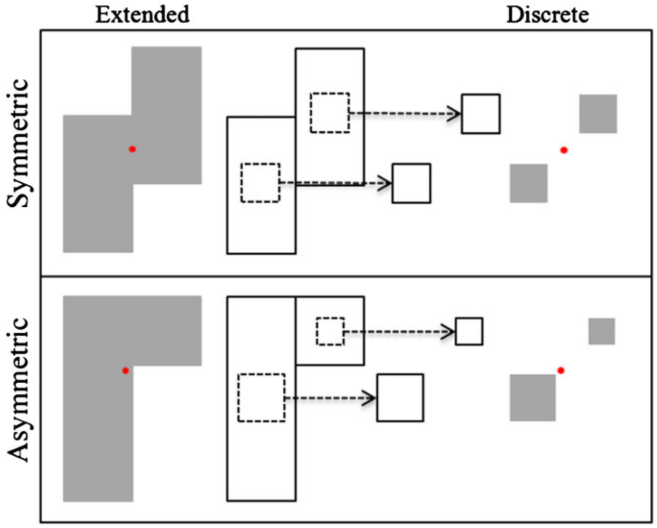

Fig. 1. Symmetry and extension of shapes.
Note: Gray figures above are examples of stimuli participants viewed during the center of gravity (CoG) task; the middle column demonstrates how the analogous discrete systems are created from the extended objects, where the ratio of the areas of the two discrete squares (selected to be simple, whole numbers ratios, i.e., 1:1, 1:2, etc.) is the same as the ratio of the areas of the two rectangles that form the extended shape. The centers (CoGs) of the two squares are separated in the computer task by the same number of pixels as the centers of the two rectangles that make up the extended shape. The (red) dots denote the actual CoG of each shape.

Procedure

After providing written consent, participants filled out a questionnaire on previous physics experience. This was followed by the CoG finding task. Last, participants were videorecorded while self-reporting (1) their perceptions of the relative difficulty of finding the CoG for different stimuli and (2) the CoG finding strategies they used.

In the CoG finding task, participants were presented with two-dimensional shapes on a touch screen device and asked to locate the CoG of the object using a stylus (see Figure 2). Shapes varied by two conditions: Symmetry (symmetric vs. asymmetric shapes) and Extension (discrete vs. extended shapes), yielding a 2 × 2, Symmetry by Extension design. Shapes consisted either of polyominoes[2] (24 extended) or two squares (24 discrete), see Figure 1. The stimuli were presented in random sequence and random position for each participant. To control for a possible effect of orientation, every extended object and its analogous discrete system was presented in four different orientations (rotation of 90° increments). This resulted in a total of 192 stimuli (48 in each condition, presented in four

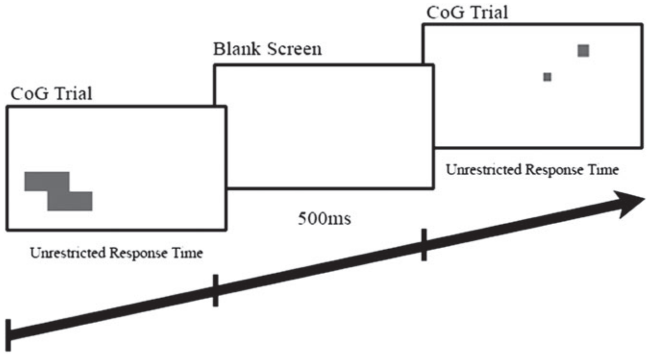

Fig. 2. The center of gravity (CoG)-finding task.
Note: No restrictions were placed upon participants' response times when finding each shape's CoG. After finding the CoG of a shape, there was a 500 ms blank slide presented, after which the next CoG shape was presented. Each CoG shape was presented at a random location on the screen, and there was never more than one CoG shape on screen at any given time. All shapes were presented on 577 × 577 pixel bitmaps, but the area of the CoG shape did not necessarily cover the entire area of the bitmap. The bitmap appeared at a random location on the computer screen. Stylus width was approximately 12.5 pixels.

orientations: Symmetric-Extended, Asymmetric-Extended, Symmetric-Discrete, and Asymmetric-Discrete).

Before starting the CoG finding task, participants were told that the CoG would be defined as "the point of balance or equilibrium of an object," and that their task was to locate the CoG of each shape. Participants were instructed to indicate the position of the CoG using the touch screen stylus as quickly and accurately as possible. Stylus click location and response time were recorded and later used to calculate error (in pixels) and response time for each of the 192 stimuli. Participants initially received five practice stimuli that included feedback from the touch screen device. The practice stimuli were unique from the experimental set, but representative of all conditions of stimuli within the task. Practice stimuli made explicit that extended shapes had CoGs located within the object itself, while discrete shapes had CoGs located outside of the two objects. A marker denoting correct CoG was immediately presented after participants made responses to practice problems.

After completing the CoG task, each participant was interviewed by an experimenter. Participants were first presented with four printed pages that included one stimulus from each of the four conditions (Symmetric-Extended, Asymmetric-Extended, Symmetric-Discrete, and Asymmetric-Discrete) and asked to rank the order of difficulty in locating the CoG for the four objects from least to most difficult. After ranking, participants described their strategy for locating the CoG of each shape beginning with the one they ranked easiest.

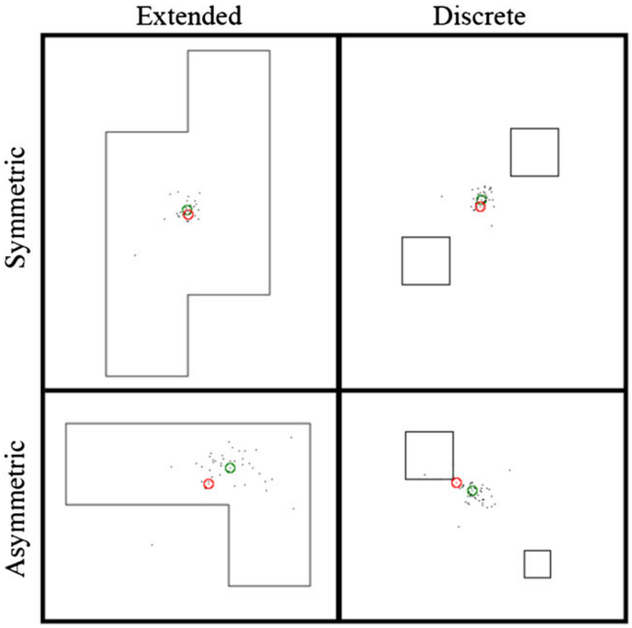

Fig. 3. Response locations on the center of gravity (CoG) finding task.
Note: All four conditions are exemplified in the above figure. Black dots represent individual participant responses. The green circles above represent the average location of participants' responses, while red circles represent the correct CoG of each figure. This figure provides a visual example of how errors for asymmetric, particularly asymmetric-extended, figures are larger compared to the rest of the experimental conditions.

RESULTS

Error

For a visualization of participants' errors within the CoG task, see Figure 3. Participants' error (i.e., distance between predicted and actual CoG in pixels) was analyzed in a 2 (Symmetry: symmetric, asymmetric) × 2 (Extension: discrete, extended) repeated measures analysis of variance (ANOVA), revealing main effects of Symmetry, $F(1,50) = 168.94$, $p < .001$, $\eta^2 = .77$ and Extension, $F(1,50) = 29.58$, $p < .001$, $\eta^2 = .37$. These main effects were qualified by a significant Symmetry × Extension interaction, $F(1,50) = 36.26$, $p < .001$, $\eta^2 = .42$ in which performance on Asymmetric-Extended objects showed the greatest error (Figure 4).

To explore whether the above-mentioned findings could be accounted for by participants' physics experience, we again performed a 2 (Symmetry: symmetric, asymmetric) × 2 (Extension: discrete, extended) repeated measures ANOVA, using the number of college physics classes reported for each participant as a covariate (i.e., an analysis of covariance, ANCOVA). Again, we found a significant main effect of Symmetry, $F(1,50) = 127.37$, $p < .001$, $\eta^2 = .72$, Extension,

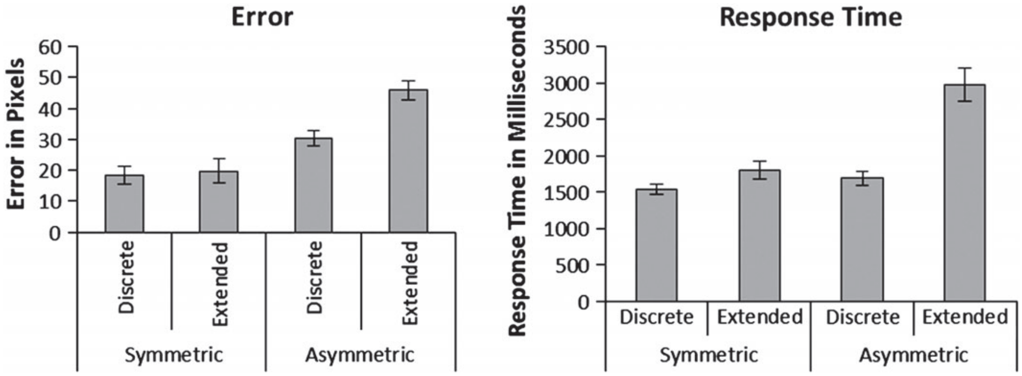

Fig. 4. Error and response times for the center of gravity (CoG) task.
Note: Error is the average distance (in pixels) from the correct CoG location. Stylus width was approximately 12.5 pixels. Errors for Asymmetric-Extended objects were approximately four times the stylus width, while errors for all other conditions were around or less than twice the width of the stylus.

$F(1,50) = 16.69$, $p < .001$, $\eta^2 = .25$, and a significant Symmetry × Extension interaction, $F(1,50) = 34.74$, $p < .001$, $\eta^2 = .42$. Errors were not accounted for by participants' physics class experience, suggesting that conceptual or knowledge-based differences among participants with more or less physics experience do not explain errors on our CoG task.

Response Times

Response time (RT) showed a similar pattern. A Symmetry × Extension ANOVA revealed main effects of Symmetry, $F(1,50) = 54.44$, $p < .001$, $\eta^2 = .52$, and Extension, $F(1,50) = 60.00$, $p < .001$, $\eta^2 = .55$, qualified by a significant Symmetry × Extension interaction, $F(1,50) = 52.78$, $p < .001$, $\eta^2 = .51$. RTs to the Asymmetric-Extended objects were nearly double the other three conditions (Figure 4). When controlling for previous physics experience, we again found a significant effect of Symmetry, $F(1,50) = 33.19$, $p < .001$, $\eta^2 = .40$, Extension, $F(1,50) = 36.46$, $p < .001$, $\eta^2 = .43$, and a significant Symmetry × Extension interaction, $F(1,50) = 30.57$, $p < .001$, $\eta^2 = .38$ in response times.

Self-Report of CoG Difficulty

We analyzed participants' rankings of CoG difficulty in the post-task interview to determine if the conditions participants reported as being easiest or hardest matched CoG task response times and errors (Table 1). Mirroring the highest error rate and response times in the Asymmetric-Extended condition, 75% of participants reported Asymmetric-Extended objects were the most difficult types of problems for which to solve CoG. Furthermore, 86% of participants reported that either of the Extended shapes (Symmetric-Extended or Asymmetric-Extended) was the most difficult. To quantify that the difficulty rankings given to Extended CoG objects were significantly different from those of Discrete CoG objects, we compared the distribution of difficulty scores that participants assigned to Discrete objects to scores assigned to Extended objects with a chi-square test of independence. Results showed that difficulty rankings for Extended objects did significantly differ from Discrete objects, $\chi^2(3, N = 204) = 35.84$, $p < .001$.

Table 1
Participants' Ranking of Center of Gravity (CoG) Difficulty

	Participants ranked as easiest (%)	*Participants ranked as hardest (%)*
Symmetric shapes	90	12
Asymmetric shapes	10	88
Discrete shapes	63	14
Extended shapes	37	86

Note: The two columns above contain the percentage of participants who reported that a shape was either easiest (i.e., ranked as "1") or hardest (i.e., ranked as "4").

In addition, 90% of participants reported that one of the symmetric conditions (Discrete-Symmetric, 59%, or Extended-Symmetric, 31%) was the easiest condition for which to solve CoG, which parallels the low error and quick response times found for the Symmetric CoG conditions. Again, we compared the distribution of difficulty rankings between Symmetric and Asymmetric CoG objects with a chi-square test of independence. Results showed that Symmetric and Asymmetric CoG objects significantly differed in the distribution of their difficulty rankings, $\chi^2(3, N = 204) = 75.53$, $p < .001$. Participants also reported using a wide array of strategies to solve for the CoG of the various objects during the post-task interview. See Table 2 for frequently reported problem-solving strategies.

Table 2
Reported Strategies on the Center of Gravity (CoG) Finding Task

Reported strategy use	*Example quote from interview*
(1) Heuristic of marking central location on symmetrical shapes	*"I just found the center point"* *"I just chose the middle to be safe"*
(2) Separating extended shapes into discrete parts	*"I was trying to break down shapes into smaller shapes that would be easier to find the balance of"*
(3) Mentally balancing the shape	*"I tried to imagine if I was trying to keep it on top of something, if I had a pencil or something and was trying to balance it* [the shape] *on it"*

Note: Shown above are strategies reported by more than 10 of the 51 participants (>20%) when solving for the CoG of various shapes. These were strategies reported of participants' own accord when not prompted through discussion with the experimenter. The final interview with participants was exploratory and did not allow for an extensive quantitative analysis of strategy use.

DISCUSSION

We show that the ability to locate the CoG of a system is influenced by perceptual characteristics of the objects involved in the task, in this case object extension and symmetry. Performance was slowest and least accurate on Asymmetric-Extended objects, a pattern reflected in participants' own reporting of the subjective difficulty of the CoG task.

Physics classroom data (Ortiz et al., 2005) have shown that student performance on questions related to CoG involving extended, asymmetric objects are significantly worse as compared to questions involving discrete, asymmetric systems. Our study removed the physics context and, while taking into account symmetry, varied shapes on two perceptual features that had yet to be directly compared with one another: discrete versus extended objects. We show that the ability to locate the CoG of shapes in a nonphysics setting is poorest when the shapes are extended and asymmetric, even when controlling for participants' prior physics experience. In other words, we show difficulties associated with perceiving extended, asymmetric objects—difficulties that could, at least in part, explain why students appear to have trouble understanding the CoG concept as it relates to similar objects in the classroom (e.g., Ortiz et al., 2005).

While our experiment was designed around manipulating perceptual features of objects within our CoG task, we also asked whether variation across participants in terms of their prior physics experience could account for our results. This was not the case. It is possible that previous exposure to CoG could either hinder or help performance on our CoG task. Students with just enough conceptual knowledge of CoG may be driven astray by misconceptions. In contrast, a high degree of physics experience could afford students the conceptual knowledge needed to overcome—at least somewhat—the perceptual difficulties inherent in our CoG finding task. Although more work is needed to test these possibilities, the current research demonstrates that there are perceptual features that create difficulties in CoG finding and suggests that these features need to be taken into account during instruction. Asymmetry and extension negatively impacted CoG performance, and this negative impact was not accounted for by students' physics experience. Addressing perceptual along with conceptual issues when teaching CoG will likely aid students' understanding.

Our findings contribute to existing research in other science, technology, engineering, and mathematics (STEM) disciplines suggesting that student performance is, in part, driven by students' perception of STEM problems rather than purely by students' understanding of STEM concepts. One example of this comes from the chemistry classroom—students' understanding and interpretation of molecules change based upon perceptual features of the presented molecule (e.g., using a Ball and Stick Model vs. a Fischer Projection; Stieff, Bateman, & Uttal, 2005). In a similar vein, students with the largest array of general spatial skills surpass their counterparts with less developed spatial skills within the geosciences classroom (Ormand et al., 2014). Basic perceptual characteristics inherent in the problems students encounter, or within the students themselves, may play a role in students' classroom performance across STEM disciplines.

In this study, students' CoG finding performance changed based on the perceptual features of the objects in question, suggesting that it is necessary to take these perceptual features into account when teaching and assessing students' understanding of the physics concepts they are tasked with mastering. The development of effective STEM teaching methods, student assessment, and classroom intervention strategies rely not only on teaching science content, but also taking into account the general perceptual features that make STEM understanding more or less difficult. And while cognitive science principles are often brought to bear in thinking about STEM learning, it is important to point out that their application is likely broader. For instance, understanding general perceptual principles may help in crafting the best pedagogical techniques for acquiring foreign languages or even grasping complex historical events. General mechanisms of human cognition are in constant interaction with the educational environment. Understanding this interaction not only allows us to optimize our teaching strategies in any given educational field, but also provides a new window within which to understand basic cognition.

Acknowledgments—This work was supported by NSF FIRE Grant (DRL-1042955), NSF CORE Grant (DUE-1348614), and Spencer Foundation Grant (201000085) to S.L.B and S.M.F.

NOTES

1 The CoG of an object or system is the point at which the entire force of gravity may be assumed to act. Center of mass is a more general term and can be different than CoG. However, the locations of the center of mass and the CoG are identical for the systems described and referenced in this article.

2 A polyomino is a pattern formed by the connection of a specific number of equal-sized squares along common edges, the most famous of which are the seven tetrominoes (number of squares, $n = 4$) familiar to any player of the popular classic video game Tetris (Fahey, 2003).

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