The Motor System Does Not Use a Curvilinear Impetus Belief: Folk Physics and Embodied Cognition

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Abstract

Previous work shows that people often believe, contrary to actual physics, that objects travelling in a curved path through a tube will continue to travel in a curved path after exiting the tube. In the present study, previous work was replicated, but accuracy increased in a new condition in which people were asked to catch an actual ball emerging from a tube. That is, in this case there is a discrepancy between how we believe the world works, and how our motor system responds to events in the world. This finding supports the theory that the perception and action systems of the brain use different methods to predict how things move in the world, and that the abstract reasoning systems used to *explain* how the world works are often in conflict with the action systems.

Introduction

People are not only brains, they are bodies too, and these bodies experience the world and the laws that govern its physics every day. Both children and adults make similar mistakes when verbally describing how they would crawl on their hands and knees – even after they have just physically crawled (Piaget, 1976). With something so fundamental to our everyday experience, we should easily be able to describe its physics and procedures. The systematic discrepancies observed between the ability to do a physical task and the inability to accurately describe or depict it has been studied under the umbrella term of folk or "naïve physics."

Since Piaget (1976) detailed several of these phenomena, one of the most notable instances of this effect is the curvilinear impetus belief: the incorrect assumption that an object travelling in a circular motion will continue this curved path upon exiting a spiral. In previous studies the average percentage of curved lines predicted had been around 36%, and 49% for participants that had no formal physics education (McCloskey, Caramazza, & Green, 1980; McCloskey & Kohl, 1983; Cook & Breedin, 1994; Freyd & Jones, 1994; Kaiser, Jonides, & Alexander, 1986).

Some have suggested that the abstractness of the task affected accuracy (Freyd & Jones, 1994; McCloskey & Kohl, 1983). For instance, when people are presented with the spiral problem on paper, but are told it is a garden hose and water as opposed to a ball and tube, they accurately predict the straight trajectory of the water, but continue to make incorrect predictions about the ball (Catrambone, Jones, Jonides & Seifert, 1995). Freyd and Jones (1994) theorized that in order to understand the abstract diagrams presented on paper, the participants may be generating abstract theories that are separate from their experiences in the real world, or on patterns of motion observed in living objects as opposed to inanimate objects. Thus, even though the problem is essentially the same, a physical example that has likely been experienced by the participants before (the garden hose), generates more correct answers. Therefore, previous experience from seeing an object in motion may be recruited to solve abstract problems. If this is true, then it would indicate that people can make good predictions about situations they have seen, but have trouble transferring that skill to new domains.

To test whether observing motion could influence accuracy, McCloskey and Kohl (1983) presented participants with 3 conditions designed to alter the degree of motion in a curvilinear task. Participants viewed three training conditions: no motion (a paper and pencil diagram), dynamic rotation (where the ball on-screen simply orbited around the circumference), and dynamic trajectory (where the ball left the orbit). The trajectory condition produced both correct and curvilinear trajectories. Surprisingly, there was no significant difference between these groups. The perceptual experiences failed to facilitate accurate trajectories. The authors argued that visual information was not sufficiently embodied to produce accurate responses.

This led to postulating whether physical touch improved the accuracy of participants' responses. McCloskey and Kohl (1983) asked participants to physically push a puck through a slightly curved 'C' shaped path. The task could be accomplished if a straight-line method was used. The task was designed to add a motor component to test whether participants used curvilinear strategies to try to complete the exercise, which would result in a failure to complete the task. Still, 25 percent of the participants demonstrated some curvilinear impetus belief, and participants who *failed* to pass the puck through the curved area with the *correct* straight-line method demonstrated on a post-test questionnaire that an alternative method might have been curvilinear. Previous research, such as work on the Ebbinghaus Illusion, showed that the physical grasping of two identically sized objects was completed accurately by the motor system, while the perceptual system simultaneously perceived one as substantially bigger. This would suggest that the action system of the brain would not be fooled by perceptual illusions (Haffenden, Schiff & Goodale, 2001). However, curvilinear impetus types of problems are not visual illusions, but internal misconceptions involving object motion, which seem to form the basis of our understanding of object physics.

Reliance on curvilinear impetus concepts today may seem counterintuitive, but in the past they were part of a dominant theory of physics in Medieval Europe. It was believed that moving objects were imbued with their own force, or impetus, that compelled them to behave in a certain way (Kozhevnikov & Hegarty, 2001). But the fact that most present-day people are ignorant of this theory suggests that these impetus beliefs are systematic and consistent between human beings. Impetus theories may provide a way of conceptualizing the world when no analogy or previous experience is accessible – a default physics in want of physical experience (Kozhevnikov & Hegarty, 2001). If this is true, then these errors should persist even when people have abstract, rule-based physics knowledge. Kozhevnikov and Hegarty (2001) tested this by giving physicists and non-physicists a spiral diagram and asking them to draw the trajectory. In one condition, participants were given as much time as they needed to answer, and in the other condition they had to answer as quickly as possible. Interestingly, both groups fell back on curvilinear impetus beliefs in the time-pressured condition. Thus, even people who possess expert physics knowledge still fall back on impetus theory when under time constraints.

There is now some evidence that impetus theories, specifically curvilinear impetus theories, are part of a default physics. However, many experiments tested impetus beliefs using abstract stimuli, and were testing the *production* or *prediction* of trajectories rather than how people *responded* to them. For instance, people do not regularly predict where water will exit from a coiled hose; however, they do respond to it physically and accurately without effort.

Many of the experiments on curvilinear impetus belief overlook the way our motor system, which tends to respond to the environment accurately, predicts the motion of objects in the world (Oberle, McBeath, Madigan & Sugar, 2005; Zago & Lacquaniti, 2005). The ability of the motor system to respond to moving objects may be an entirely embodied phenomena, one that has been explained with complex abstract terms, but is easily accomplished with simple, embodied perception-action rules (Wilson & Golonka, 2013).

For instance, complex motion problems like the outfielder problem can be easily explained with perception-action rules, rather than with abstract, representational explanations. The outfielder problem asks the question, 'how does an outfielder know where to be to catch a fly ball?' The traditional cognitive approach would suggest reasoning based on a model or rules—for example, that the outfielder calculates initial speed and angle, and uses laws of projectile motion to predict where the ball will land and moves there in a straight line. The embodied approach, on the other hand, would state that as the outfielder moves, they utilize a combination of their motion through space as well as the ball's motion through space. The embodied approach claims that the outfielder simply follows two elementary, perceptually based rules; first, move in a curved path that mirrors the path of the ball, so that it appears that it is moving in a straight line, and second, match speed so that it appears that the ball is moving at a constant velocity (Wilson & Golonka, 2013). Furthermore, most outfielders run in curved lines. There have been many elaborations on these simple embodied rules to catch a fly ball that rely entirely on reactionary rules (Chapman, 1968; McLeod, Reed, Dienes, 2006; Tresilian, 1995). To further add to the evidence that the motor system responds in real time to the environment, rather than following a previously simulated prediction, outfielders can catch fly balls in virtual reality whose paths actually defy physics, where it is impossible to predict trajectories (Fink, Foo & Warren, 2009).

The apparent discrepancy between the motor system responding to a trajectory and the abstract prediction or production of one could explain why multiple studies report surprisingly high prediction errors in schematized spiral problems. This effect may be due to there being separate pathways for perception and action of visual stimuli (Goodale & Milner, 1992; Haffenden, Schiff & Goodale, 2001). For example, when a ball is dropped from a certain height, regardless of the weight, participants will react accordingly and catch the ball, and their implicit motor knowledge will even account for the mass by demonstrating stronger muscle activity in anticipation of a heavier object (Oberle et al, 2005; Zago & Lacquaniti, 2005). Interestingly, the same participants will make incorrect Aristotelian assumptions about which ball will hit the ground first when posed the question abstractly, but will demonstrate implicit motor knowledge of Newton's Laws of Dynamics when responding physically. These results demonstrate that the motor system is responsible for accurately responding and accomplishing a task that the same participants are unable to accurately describe conceptually.

This discrepancy between being able to do something and being able to accurately describe it has produced some interesting theories to account for it. Rather than the embodied/abstract distinction, Tresilian (1995) proposes a dual system of object motion that is treated separately in the mind, using different mechanisms to process information: the cognitive-perceptual and the action-oriented. The cognitive-perceptual pathway would deal with more abstract information, based on prediction or using rule-based algorithms, whereas the action-oriented pathway mirrors what embodiment researchers have called the perception-action loop. This action-oriented pathway would consist of simple, automatic, and reactionary rules that utilize relational information between the body and the environment – information that sophisticated robots use to locomote or otherwise interact with their surroundings, or how an outfielder catches a fly ball (Raibert et al., 2008, Tresilian, 1995; Wilson & Golonka, 2013). Tresilian proposed that we naturally conceptualize the world via the cognitive-perceptual pathway, and physically respond to the world via the action-oriented pathway. The errors observed in folk physics research may be due to the cognitive-perceptual pathway processing information that is more naturally suited to processing by the action-oriented pathway. In Tresilian's model, the errors that are observed in curvilinear impetus belief problems are the result of the cognitive-perceptual pathway being forced to perform an inherently artificial task that it is not biologically suited to, whereas a real spiral and ball would have the action-oriented pathway perform as intended – quickly, accurately, and situated in the real world. Thus, a cognitive-perceptual pathway set opposite to an action-oriented pathway would account for all types of object motion perception, as well as the errors observed in the literature.

The goal the present study was to test the distinction between the cognitive-perceptual pathway and the action-oriented pathway by systematically increasing the degree of embodiment on variations of the spiral tasks used in McCloskey et al. (1980). The curvilinear impetus belief was tested in the abstract sense on paper, as well as in an embodied sense where participants were instructed to reach for a ball as it rolled out of a physical spiral. An intermediate condition was presented so that the spiral device was present, but the participant chose from multiple-choice correct and incorrect trajectories drawn on paper in front of the physical spiral. We hypothesize that, in the abstract condition, the brain will use the cognitive-perceptual pathway, which will result in many errors. In the prediction condition, both the cognitive-perceptual pathway and the action-oriented pathway will be engaged, which will result in fewer errors. In the action condition, only the action-oriented pathway will be engaged, resulting in the fewest errors of the three conditions.

Method

The first group of participants were given a diagram from McCloskey et al. (1980) to control and replicate the findings, and to provide an *abstract* condition. They were asked to draw the trajectory of an imagined ball exiting a spiral on the diagram.

The second group was presented with a spiral device designed to carry a small metal ball, and the participants were asked to select a labeled trajectory similar to McCloskey and Kohl (1983), thus providing data for a *prediction* condition between abstract and action conditions, as the spiral no longer had to be imagined but was physically instantiated in front of them.

Participants in the third group, the *action* condition, were presented with the device and were asked to catch the ball as it exited the spiral. We recorded the distance from their hands to the correct trajectory of the ball.

All responses were recorded categorically as correct or incorrect.

Participants:

A total of 72 adults, all undergraduate students were recruited to participate from February 28, 2015, to November 27, 2016 through the online recruitment site at Carleton University in exchange for extra credit in a class. Two participants were excluded from the dataset due to a misunderstanding of the instructions. From the remaining participants, there were 40 females and 30 males. The average number of physics courses taken was 1.6, and the average year of university of the participants was 2.2. Participants were split into three groups: an abstract condition, a prediction condition, and an action condition. There were 24 participants for the abstract condition, 23 for the prediction condition, and 22 for the action condition, with a mean age of 20.6. All participants had normal or corrected to normal vision.

Materials:

Participants in the abstract condition were provided with a pen, and a spiral diagram that was used in McCloskey et al. (1980) on 8.5" x 11" white standard weight paper.

The prediction and action conditions were presented with the physical device sitting on a table, positioned approximately 45cm to the left of the participant. The device was 90cm tall, with a diameter of 44cm (See Figure 3). For the prediction condition, the device was set alongside pre-drawn predictions of correct and incorrect trajectories on a large sheet of 61 x 90.2 cm graph paper, placed so that they appeared to emerge from the exiting end of the tube. The spiral was made of one inch clear tubing, 3-inch PVC pipe, and wood fittings. The metal bearing used in Condition 3 weighed 28.3 grams.

To determine where the participants were reaching in Condition 3, a Nikon P7700 Powershot video camera was placed above the area on a tripod so as to include the participant's hand, as well as 1-inch measurement marks to measure correct or incorrect responses.

Stimuli:

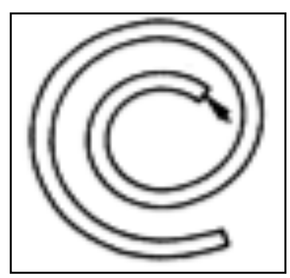


Figure 1: Spiral figure for the Abstract condition

The stimuli for the abstract condition was taken from McCloskey et al. (1980) in order to verify that the groups of students used in our experiment produced similar errors to the students in the previously mentioned paper, as well as provide data for an abstract condition (Figure 1).

In the prediction condition, participants were seated in the same orientation to the apparatus as the action condition to select from set trajectories. The participants were presented with the spiral apparatus (rather than solely a picture) and were asked to verbally make a selection from the set of predefined trajectories. The trajectories were taken from the most likely errors in McCloskey et al. (1980) that were subsequently used in the multiple-choice condition in McCloskey and Kohl (1983) (Figure 2).

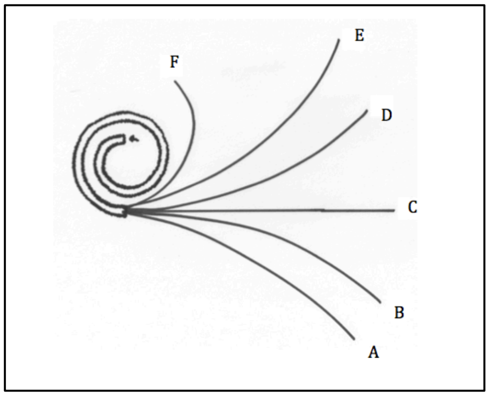


Figure 2: Spiral figure used in conjunction with spiral device for the Prediction condition

In the action condition, participants were presented with the spiral apparatus and were asked to catch the ball as it exited the tube (Figure 3). A camera was employed to measure the reactions and catalogue the accuracy of the motor response.

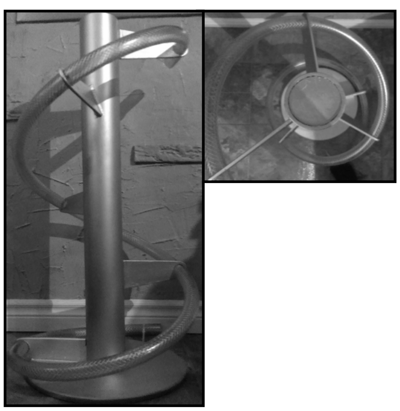


Figure 3: Spiral device for the prediction and action conditions. Side view (left) and top view (right)

Procedure:

In the abstract condition, the participants were presented with a paper and pencil test with the diagram from McCloskey et al. (1980), hidden beneath the short demographic questionnaire. They were then given the following instructions:

"This diagram is intended to show a curved tube. In the diagram you are looking down on the tube from above. A metal ball is put into the end of the tube indicated by the arrow. The ball is then shot out of the other end. Your task is to draw the path the ball will follow after it comes out of the tube. Please flip the page and proceed."

In the prediction condition, after completing the questionnaire, the participants were shown the physical apparatus and were asked to choose from 6 set trajectories from McCloskey and Kohl (1983). The participants in this condition were instructed as follows:

"This device will allow a small metal ball to travel down the tube. The ball will then exit the tube and travel on its trajectory. Your task is to pick which labeled trajectory the ball will most likely follow without using your hands. Please verbally indicate your answer."

In the action condition, after completing the questionnaire, the participants were shown the physical spiral device and given the following instructions:

"This device will allow a small metal ball to travel down the tube. Once the ball is inserted into the tube, your task is to reach for the ball only when it passes the marked area in red so as to catch it in the palm of your hand. Please move your hand in a straight line away from you."

Participants were asked to wait until the ball had passed the marked area so that their hand would have to move late and fast, to prevent them from moving their hand in response to the *perceived* trajectory—we wanted to measure where their motor system thought the ball would go, not how it might change trajectory on the fly.

Measures:

We counted any curved lines drawn in the abstract condition as erroneous and took them to indicate a curvilinear impetus belief. Similarly, we categorized as incorrect any curved responses selected in the prediction condition.

In the action condition, we coded any deviations away from the correct trajectory as erroneous. This was accomplished by measuring, on the video, how far the participant's knuckle on the index finger was from the correct trajectory. When the participants reached for the ball after it had passed the marker, any deviations from the correct trajectory exceeding 1 inch away from the zero line were recorded as errors. If while attempting to catch the ball, the knuckle of the hand was within one inch on either side of the zero line, the response was categorically correct.

Design:

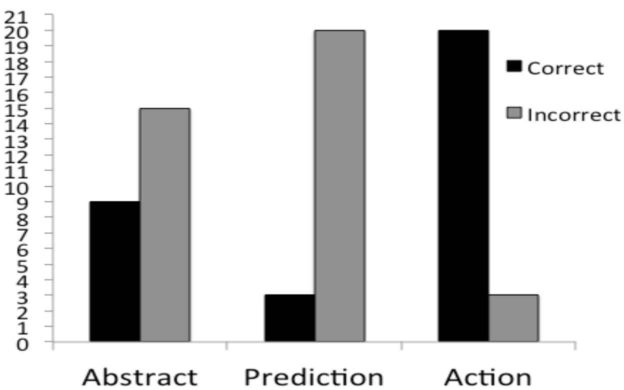
Participants were assigned to the three conditions in the order of abstract, prediction and action, in a between subjects design. A Chi Square Test for Independence was conducted for all three conditions, and between paper and prediction, paper and action, and prediction and action as post hoc analyses. The number of physics courses was split into three arbitrary groups of None (0), Some (1-3), and Many (3 or more), and were analyzed with the Chi Square test for independence as well. All post-hoc tests were corrected using the Bonferroni correction.

Results

Participants in the action condition, where people actually reached for the ball rolling out of a curved tube, were much more accurate than participants who merely predicted the path of the ball on paper.

Over all three conditions, the accuracy of responses differed significantly between the conditions, though not in the predicted increasing fashion. A Chi Square test for Independence between the three groups produced $\chi^2 = (2, N = 68) = 26.31$, $p < .001$, *Cramer's V* = .43, which is statistically significant and indicates a large effect size.

Figure 4: Number of Correct and Incorrect Responses per Condition



Post hoc analysis illustrates that the main effect, between all three conditions, was primarily driven by the difference between the prediction condition and the action condition, as can be observed in Figure 4. Post hoc testing using the Bonferroni Correction for pairwise comparisons with the Chi Square test determined that there was a significant difference between the abstract and prediction comparison, $\chi^2 = (1, N = 47) = 10.55$, $p < .017$, the abstract and action comparisons, $\chi^2 = (1, N = 47) = 16.42$, $p < .017$, as well as the prediction and action comparisons, $\chi^2 = (1, N = 46) = 25.66$, $p < .017$.

There was no relationship between the number of physics courses taken, $\chi^2 = (2, N = 70) = 1.59$, $p = .45$. Post Hoc tests with the Bonferroni Correction also revealed no significant differences between groups, $p > .017$.

Discussion

These results have provided some support for the original hypothesis that the degree of embodiment significantly influences the accuracy of responses. However, we did not observe the stepped increase from the abstract condition to the action condition. There was no effect of the number of physics courses on the number of correct responses, which supports Kozhevnikov and Hegarty's (2001) finding that physicists and non-physicists alike seem to rely on an incorrect default curvilinear physics for abstract problems. In the abstract condition, 62.5% of the respondents produced incorrect trajectories compared to the 36% and 49% reported in McCloskey et al. (1980).

The original hypothesis that the difference between the abstract condition and the action condition would produce significantly different responses was supported. Surprisingly, however, the prediction condition had the fewest correct responses, with most participants choosing between two of the 6 options (E and D in Figure 2), whereas it was hypothesized that the prediction condition would have more correct responses than the abstract condition. Lastly, the action condition had the most correct responses, which supported our hypothesis that there is a dissociation between our action-oriented pathway and our cognitive-perceptual one.

With this paradigm in mind, the finding that many of the prediction condition responses were incorrect might be explained by the fact that both the cognitive-perceptual and the action-oriented pathways were in conflict, causing more errors. Alternatively, there was no participant motion involved, and this lack of a motor aspect in the prediction condition might have hindered its validity as a medium embodied condition. Also, the relatively high number of correct responses in the action condition suggests that physical responses are more biologically adapted for accuracy. Taking these findings into account, the act of drawing in the abstract condition may have allowed the action-oriented pathway to provide more correct paths of the imaginary ball, while the stationary aspect of the prediction condition may have only allowed the cognitive-perceptual pathway to be used. Thus, the abstract condition may have been more embodied than the prediction condition, which if true, would demonstrate the stepped increase hypothesized.

The significant differences observed in this experiment have illustrated the degree to which our minds are divided depending on the task and level of physical action. However, future research could expand the prediction condition of this experiment by investigating how participant motion, for example pointing to the correct trajectory or producing it alongside the spiral might increase the number of correct responses by activating the action-oriented pathway. Other areas of research may include asking participants to *imagine* the trajectory of the ball before choosing or drawing their prediction, to more accurately determine the capacities of the cognitive-perceptual pathway. Furthermore, the method for coding accuracy was done categorically and was measured differently between conditions, posing some reliability concerns. Because of these limitations, future projects should investigate the production of the trajectories, as in the abstract condition, in a setup identical to the prediction and action conditions, thereby increasing the generalizability of the results.

The implications of this research are broad. The pedagogical implications for teaching elementary physics could be substantial. Participants were largely incorrect when presented with abstract, as well as non-dynamic examples of this physics problem (i.e. prediction condition), so it might be beneficial for educational authorities to encourage more embodied examples of physics problems to facilitate student understanding. The results partially support Tresilian's (1995) model that the cognitive-perceptual pathway demonstrates poorer performance on abstract physical tasks, whereas the action-oriented pathway does better on responsive and physical tasks.

These results have provided evidence for one of the cornerstones of embodied cognition: that cognition evolved for action (Wilson, 2002). This is not usually the case in many research papers, as much embodied research that is publically received involves associations between mental representations and bodily postures, types of movement, and even the types of clothes people wear (Adam & Galinsky, 2012; Markman & Brendl, 2005; Reutner, Hansen, & Greifeneder, 2015). Although the results from these associational studies are interesting, they support a weaker version of embodied cognition; one that implies that cognition is merely influenced by the brain, the body and the environment. This study suggests a distributed view of the mind, one that engages the action-oriented pathway when solving embodied motion problems, yet falls back on the cognitive-perceptual pathway when motion is absent.

At present there is evidence for a dual-pathway system: one utilized when the mind is processing abstract conceptualizations, and one that utilizes the motor system when the mind is processing motion problems, using perception-action loops in a reactionary fashion. The classical view of the mind within cognitive science as a symbol manipulator falls apart when real world motion is involved, and embodied cognition and Tresilian's dual pathway system for object motion may provide a new way of conceptualizing how minds react and think about object motion.

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