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The representation of naïve knowledge about physics

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Human beings rely on visual information to learn about the environment around them, construct representations of the world, and control their actions. By and large, humans are remarkably accurate when it comes to complex motor actions such as catching a baseball or hitting a target. In fact, the perceptual skills underlying such actions are not easily understood as they are far superior to any visual information processing capability of artificial systems constructed to date. In stark contrast to our excellent perception-action abilities, there are conditions under which humans make striking judgment errors that are at odds with the visual information experienced.. We will describe some examples of such errors in a large proportion of the population suggesting that knowledge of the physical world is represented poorly in the cognitive domain. We will discuss some explanations for this phenomenon, and explore the implications for a scientific study of visual representations and interpretations.

1. A BRIEF INTRODUCTION TO NAÏVE PHYSICS

Naïve physics is the name given to the field of study into our common-sense beliefs about classical mechanics, as relevant to our actions. Naive beliefs are often found to be at odds with reality. For instance, when asked where to drop a ball to hit a target on the floor while moving in an airplane or on a conveyor belt (Kaiser, Proffitt, Whelan & Hecht, 1992; Krist, Fieberg & Wilkening, 1993; McCloskey, Washburn & Felch, 1983), many adults state that they should release the ball right above the target. This belief immediately turns out to be mistaken when actually doing the task. Even children quickly adjust once they see that they overshoot. However, the mistaken "straight-down belief" remains in place. Similarly, when a marble's motion upon exiting a C-shaped tube lying on a tabletop has to be predicted, many adults mistakenly predict a curved exit path. The same people, upon observing curved paths in manipulated video animations, immediately notice that straight paths look much more natural.

In essence, naive physics can only be understood if we conceive of the representation of elementary laws of physics in a modular way. Three representational subsystems represent

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knowledge with little or no cross-talk. Action representations are accurate to the extent needed and as a function of how costly it is to correct an action. Perceptual representations are often but not always superior to cognitive representations. And the latter - strangely - fare worst. To better understand the evidence for this modular view, we describe from a historical perspective intuitive physics findings in general and then focus on the new field of intuitive optics.

The first appearance of the term "naïve physics" is believed to be in a book by Lipmann and Bogen in 1923, referring to the interaction with the physical world in everyday tasks. The idea to empirically investigate beliefs and concepts about the physical world was picked up and explored by the Gestalt school of psychology (we can include in this the classic work with chimpanzees by Köhler, 1921). An exploration of naïve mechanics was carried out in the 1950's by Bozzi, but this work was not published in major journals (see Bozzi, 1990, Pittenger & Runeson, 1990, and for more historical notes see Smith & Casati, 1994). The term "naïve physics" has also been used in the field of artificial intelligence (for a manifesto see Hayes, 1979). A technique known as "knowledge engineering", based on introspection, is employed to formulate descriptions of world-knowledge in the language of formal logic (see Davis 1990 for a good example, particularly Chapter 7). Such research aims to provide a foundation of knowledge for use in robotics (Hayes, 1979).

Within the cognitive sciences, the field of naïve physics studies the common-sense beliefs that people hold about the way the world works (as defined by Proffitt, 1999, in the MIT encyclopaedia of cognitive sciences, see also McCloskey, 1983, who calls it "intuitive physics").

Although in theory naïve physics may be explored for all natural phenomena, particular attention has been given to classical mechanics (Bozzi, 1990; Proffitt, 1999; Shanon, 1976). It is probably non-controversial that classical mechanics does offer the most relevant examples, because the importance of other aspects of physics, such as quantum mechanics, can only be appreciated in the small scale of subatomic physics or large scale of astrophysics. Neither of these domains are easily accessible to people's everyday experience of a world of middle-scaled objects (i.e., from a few millimetres to a few kilometres) (on this see also Gibson, 1979). Because of the amount of experience that human beings have with the physical phenomena in the environment described by classical mechanics, it is intriguing that in many instances people hold beliefs that are not just underdeveloped but systematically wrong. For example, people can aim projectiles accurately (e.g., throwing a ball) but have difficulty drawing the shape of path that projectiles take (Caramazza, McCloskey, & Green, 1981; Clement, 1982; Kaiser, Jonides, & Alexander, 1986; Kaiser, Proffitt, & McCloskey, 1985; Krist, Fieberg, & Wilkening, 1993; McCloskey, Washburn, & Felch, 1983). Furthermore, physical expertise does not always improve naïve understanding. For example, about 40% of adults predict the orientation of a liquid surface in a tilted but stable glass to be more than 5 degrees away from horizontal (McAfee & Proffitt, 1991). Expert liquid handlers, such as the professional barstaff at the Oktoberfest, exhibited even larger errors (Hecht & Proffitt, 1995).

Mistaken beliefs are not only present when abstract questions are asked out of context, but also extend to cognitive, perceptual, and developmental aspects of knowledge. For example, it is physically true that a pendulum will take the same amount of time to swing through its arc, however wide the arc (deviations are small for all practical purposes). However, Bozzi found that people will only perceptually accept certain speeds that appear "natural" to them, and for long arcs pendulums appear unnaturally fast (Pittenger & Runeson, 1990). Galileo himself only came to believe in the isochronism principle (fixed period) after empirical observations and never failed in his writings to point out how this was true even though it was counterintuitive (Bozzi, 1990). For projectiles, evidence that perceptual knowledge of natural motion is better than abstract knowledge is for instance in Kaiser, Proffitt, and Anderson (1985) but see Hecht and Bertamini (2000) for a case in which perceptual judgment about projectiles is incorrect.

With respect to the mistaken beliefs about mechanics two lines of explanation have been developed. On the one hand our intuitions may evolve slowly, and our naïve beliefs may not have progressed beyond the level of Aristotelian physics, unable to follow the advances of modern physics (Bozzi, 1990; Caramazza, McCloskey & Green, 1981; McCloskey, Washburn, & Felch, 1983; Shanon, 1976). The alternative explanation is that naïve physics reflects capacity limitations in people's reasoning process (Kaiser, Proffitt & Anderson, 1985; Proffitt & Gilden, 1989). It is suggested that people even when people know all relevant dimensions or properties in isolation, they fail to integrate them when forming representations of complex events. These incomplete representations are then applied to novel situations, in which the outcome is therefore inaccurately predicted. It has also been demonstrated that representations of events can incorporate too many properties: People appear to believe that the accelerating properties of a thrower's arm will remain in the ball after it has been thrown, and therefore continue to accelerate (Hecht & Bertamini, 2000).

What is common to all of these examples is the fact that experience of extremely familiar events, such as the motion of a thrown ball, does not always lead to correct knowledge (either abstract or implicit) about the underlying principles (Hecht & Bertamini, 2000). Furthermore, and surprisingly, some of these mistaken beliefs are strengthened rather than weakened by experience (e.g., Hecht & Proffitt, 1995).

In the rest of this paper we shall do two things. Firstly, we shall briefly outline new results from our laboratory that extend the field into what we call naïve optics. Secondly, we shall discuss the need for the field of naïve physics to systematically explore the differences between the following three levels of representations: Naïve beliefs - accessible through introspection; Perceptual knowledge - tested by inspecting people's ability to recognise deviations from the laws of physics in simple physical phenomena; Action knowledge - tested by looking at what people can and cannot do. We propose that a comparison of these three levels is essential to understanding the structure of visual representations. For example, the existence of conflicting representations within the individual may reflect a modular system of representations, with far-reaching impact in the study of any system, human or artificial. Neurophysiological evidence already suggests that parallel systems do exit in humans to control visual recognition and to guide visually controlled action (Milner & Goodale, 1995).

As was pointed out earlier, the field of naïve physics has previously focussed on mechanics. This is reasonable since so much of what is relevant for human behaviour depends on the laws of mechanics, from walking to trying to hit a prey with a projectile. However, recent work has expanded the field to cover some aspects of physical optics (Croucher, Bertamini & Hecht, 2002; Bertamini, Spooner & Hecht, 2002). Although it is true that light as such is never directly the object of our experience (Gibson, 1979), a large amount of human behaviour depends indirectly on the laws of optics. For instance, what is made visible by a mirror depends on the laws of reflection, because it depends on the way light travels and bounces in the environment before reaching our eyes. Therefore knowledge about mirrors may be derived from an understanding of the laws of optics (and vice versa) (Croucher, Bertamini & Hecht, 2002). In the next section we will summarize a set of naïve optics findings. As will become clear, in common with naïve mechanics our representations of reflections are surprisingly inaccurate given our wealth of experience.

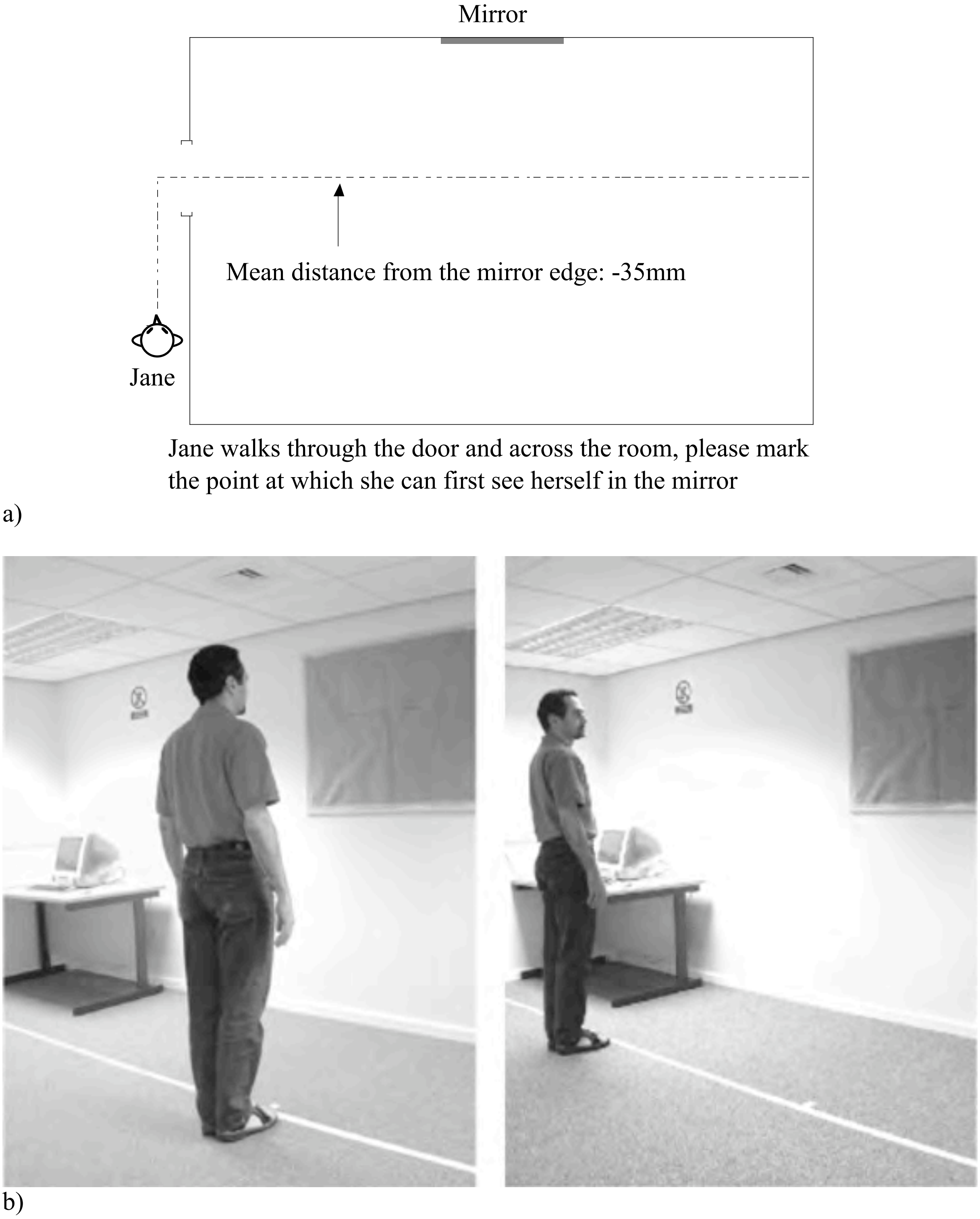
2. NAÏVE OPTICS FINDINGS

Surprisingly few common-sense beliefs about light and optics have been studied although there is indication of blatant errors. For instance, many children and even adults believe that the eyes emit rays or objects. This extromission belief was prevalent in ancient Greek philosophy (Cottrell & Winer, 1994; Winer & Cottrell, 1996; Winer, Cottrell, Karefilaki & Chronister, 1996). In this section we will summarise new findings in a related area, the intuitive understanding of mirror reflections (Croucher, Bertamini & Hecht, 2002). In summary, many participants made significant errors when asked to indicate where an observer would be able to see a target in a mirror.

In a set of experiments, participants were presented with a diagram of a room on paper (see Figure 1a), and were asked to mark where on the paper a character (Jane) would first see her reflection in a mirror. The correct answer in Figure 1a was that Jane would have to be level with the near-edge of the mirror. However, participants tended to predict that Jane would see her reflection when she was still some distance to the side of the mirror. This consistent error remained when participants were asked to position themselves so that they could just see their own reflection in a pretend (non-reflective) mirror (see Figure 1b). People tend to believe that they would see themselves in mirrors before they actually would (Croucher, Bertamini, & Hecht, 2002). This finding is intriguing, since people have a wealth of experience walking over to mirrors to view their reflections. Furthermore, we found that this error extended to predictions regarding when another object becomes visible in a mirror. This was true whether the object was stationary while the observer moved or vice versa.

Croucher Bertamini and Hecht (2002) considered four possible explanations of this consistent error. (a) *Egocentric mirror rotation hypothesis*: Observers may have failed to take the orientation of the mirror surface into account and they may have treated the mirror as a surface (approximately) orthogonal to their line of sight. (b) *Capture hypothesis*: Mirrors may be conceived as pictures which capture images for further inspection, so that the location of the observer is irrelevant. (c) *Boundary extension hypothesis*: People may perceive (and remember) a larger amount of the virtual space than is actually visible in mirrors. There is evidence that something similar happens for photographs, and this phenomenon is known as "boundary extension" (Intraub, 1997; Intraub & Bodamer, 1993). (d) *Left-right reversal hypothesis*: People have some understanding that there is some left-right reversal in mirrors, and may extrapolate from this incomplete representation to expect complete reversal of the imagined visual space around a vertical axis, thus misplacing objects in the mirror reflection (Gregory, 1997). People would then predict an observer's reflection to appear from the left as the observer approaches from the right, and in turn this may lead to an overestimation of what is visible from the side (Bertamini, Spooner & Hecht., 2002).

There is some evidence to support all four of these hypotheses, and experiments are under way to test them more directly. The actual outcome may be a combination of all of them (Bertamini, Spooner & Hecht, 2002). We expect that the complex pattern of results will be explained only by a careful examination of the three levels of representations mentioned earlier: naïve beliefs, perceptual knowledge and action knowledge with relation to mirrors.



Jane walks through the door and across the room, please mark the point at which she can first see herself in the mirror

Figure 1. The two tasks used in Croucher, Bertamini Hecht (2002). a) An example of an item from a paper-and-pencil task, including a grey line showing the correct answer, and an arrow showing the mean response. b) Photographs of the room used in the pretend task. In the second image the person is standing at the average distance chosen by the participants (70cm away horizontally from the mirror edge).

That important differences must exist is already suggested by the fact that the large prediction errors (naïve beliefs) that we have documented do not seem to lead to a lack of usefulness of mirrors in controlling actions such as shaving or driving a car (action knowledge). Moreover, the studies underway in our laboratory also test whether these mistakes extend to perceptual knowledge. In other words, whether people would be able to select a correct mirror reflection as the most "natural" reflection (Bertamini, Spooner & Hecht, 2002).

3. TYPES OF TASKS AND TYPES OF REPRESENTATION

We have seen that there are accepted definitions of naïve physics, but it is also fair to say that the question of what knowledge about the world we display in our beliefs, perceptions, and action is a broad one, and much overlap exists with other areas. In this paper we have briefly summarised some findings, and in particular we have reported recent developments that go beyond classical mechanics (Croucher, Bertamini & Hecht, 2002). In this section we reflect on the importance of the study of visual representations and interpretations as they are revealed by all three main types of tasks used in the naïve physics literature: Open questions as well as some paper-and-pencil tasks test explicit (naïve) knowledge and beliefs; Judgments about what looks "natural" test what we have called perceptual knowledge; Setting specific tasks that need to be carried out by visually controlled actions tests what we have called action knowledge. Empirical evidence has demonstrated that conflicting beliefs can co-exist in the individual across these three levels of representation.

Research in cognitive neuroscience has led to what is known as a theory of two visual systems (for a well documented synthesis see Milner & Goodale, 1995, another recent review is in Creem & Proffitt, 2001). Milner and Goodale suggest that one system is mainly involved in the processes of recognition and identification (they call it the "what" system). Another system is responsible for mapping the location of objects, and is involved in the visual control and guidance of motor behaviour (the "how" system) (see also the distinction between *pragmatic* and *semantic* representations in Jeannerod, 1997). Work on the issue of the two visual systems with normal participants has already shown that it is often a subtle change in the task that can change the nature of the outcome completely. For instance, when judging the inclinations of hills people make large mistakes. A 5 degree hill appears to be about 20 degree to the average observer (Proffitt, Bhalla, Gossweiler & Midgett, 1995). People make these mistakes any time they rely on a stored representation of the scene (for instance after a delay). However, people are accurate when they use an immediate motor response, such as when they use their hand to match the inclination of the slope, while still looking at the slope (Bhalla & Proffitt, 1999).

In the present context we are suggesting that this new way of understanding apparent incompatibilities in knowledge can help us explain what is quite so surprising in naïve physics. People can be systematically wrong about laws of mechanics (and optics) to which they have been exposed throughout their lives, and even presenting observers with physically possible and impossible events does not always allow them to amend their judgment and recognise the correct event (e.g., Bertamini, Spooner & Hecht, 2002 Hecht & Bertamini, 2000; Pittenger & Runeson, 1990; Proffitt, 1999). However, the existence of systematically wrong beliefs about the physical world does not get in the way of people interacting successfully with it. Climbing slopes, carrying glasses full of beer, throwing balls, and shaving using a mirror are extremely complicated tasks for a machine but are almost trivial for human beings, although the machine may know the mechanical rules but the human does not. The work we have reviewed in naïve physics has demonstrated a clear distinction between what we know and what we can do. While people are bad at drawing or recognising correct trajectories, they appear to use another system to guide the ball to the basket. Conversely, extensive training as a structural engineer will not raise your chances of getting all your beer across a busy pub. Likewise, observers who grossly misjudge the location of a mirror image when asked to make a prediction are likely to use their car's rear view mirror successfully. Knowledge about basic laws of physics, it is starting to appear, is only useful if represented at the correct level for the task at hand. Moreover, it appears that the action system experiences the strictest validations whilst the cognitive system, and to a smaller degree the perception system, are less curtailed by reality.

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