Beyond Illusions

On the Limitations of Perceiving Relational Properties

Heiko Hecht

Explaining the perception of our visual world is a hard problem because the visual system has to fill the gap between the information available to the eye and the much richer visual world that is derived from the former. Perceptual illusions continue to fascinate many researchers because they seem to promise a glimpse of how the visual system fills this gap. Illusions are often interpreted as evidence of the error-prone nature of the process. Here I will show that the opposite is true. To do so, I introduce a novel stance on what constitutes an illusion, arguing that the traditional view (illusion as mere discrepancy between stimulus and percept) has to be replaced by illusion as a manifest noticed discrepancy. The two views, unfortunately, are not necessarily related. On the contrary; we experience the most spectacular illusions where our perception is pretty much on target. Once our interpretation of the sensory data is off the mark, we usually no longer experience illusions but live happily without ever noticing the enormous perceptual and conceptual errors we make. The farther we move away from simple pictorial stimuli as the subject of our investigations, the more commonplace a discrepancy between percept and reality does become—and the less likely we are willing to call it illusory. Two case studies of our perception of relational properties will serve to illustrate this idea. The case studies are based on the conviction that perceiving is more than mere sensation, and that some degree of (unconscious) judgment is a necessary ingredient of perception. We understand little about how to balance objects and we make fundamental mistakes when perceiving the slipperiness of surfaces. All the while, we never experience illusions in this context. Thus, when dealing with simple percepts, illusions may be revealing. But when it comes to percepts that involve relational properties, illusions fail to arise, as perception is not concerned with veridicality but appears to be satisfied with the first solution that does not interfere with our daily activities.

Keywords
Error | Illusion | Intuitive physics | Underspecification

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1 Illusion?

1.1 The underspecification problem (UP)

Visual perception can be seen as the process by which the visual system interprets the sensory core data that come in through the retinae of the eyes (see e.g., Hatfield & Epstein 1979). The sensory core is not sufficient to specify the percept; that is, there is an explanatory gap between the information present at the retina—which is in essence two-dimensional (2D)—and the information present in the three-dimensional (3D) objects that we see. Let us call the problem that arises in having to fill this gap the "underspecification problem" (see Hecht 2000). Figure 1 illustrates the UP (underspecification problem). A given object can only project one particular image onto the projection surface (retina); however, a given projection could have been caused by an indefinite number of objects in the world. Because of this anisotropy in the mapping between the 3D object and its 2D projection, information is lost during the projective process, which cannot be regained with certainty. One could argue that the history of perception theories is more or less the history of finding solutions to reconstruct the 3D object that has caused a given projection.

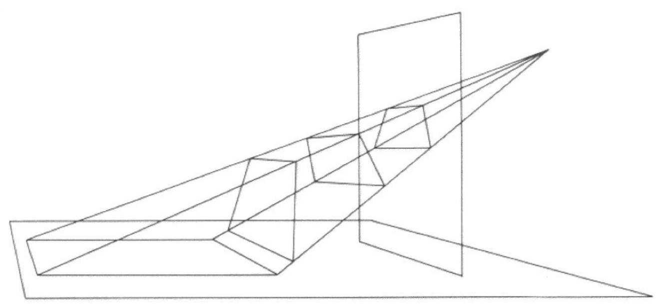

Figure 1: Underspecification: The 3D origin of a given image on the retina (here approximated by the vertical projection screen) is provided by an indefinite number of objects at various orientations in space. Illustration from Gibson (1979).

In order to assess the quality of the solution offered by a given perceptual theory, we have to evaluate how it describes the gap between sensory core and percept and the mechanism by which it suggests that the gap is being bridged. The Gibsonian theory of direct perception aside—which denies the problem altogether (e.g., Gibson 1979)—we have a variety of theories to choose from. They are all constructionist in the sense that the sensory data have to be interpreted and arranged into the configuration that is most likely or most logical. The theories differ in the mechanisms they make responsible for the reconstructive process. For instance, Hermann von Helmholtz (1894) supposes inferences of unconscious nature that arrive inductively or maybe abductively at a preferred solution. Roger Shepard (1994), on the other hand supposes a recurrence to phylogenetically-acquired knowledge. He takes the regularities of the physical world or of geometry to have been internalized through the course of evolution and to be used to disambiguate competing solutions. An example of such internalized knowledge is the fact that light usually comes from above (see Figure 2). A shading gradient from light (at the top of an object) to dark (at its bottom) would thus be compatible with a convex but not with a concave object.

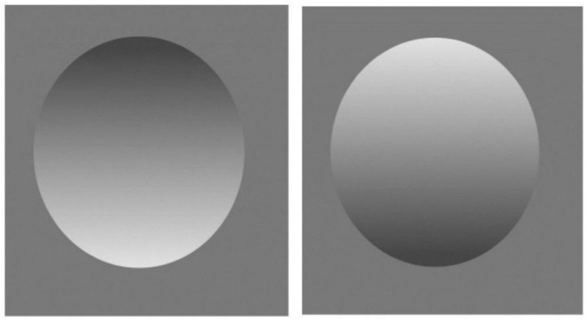

Figure 2: Solution of the underspecification by drawing on internalized knowledge that light comes from above. The sphere in the right panel looks convex because it is lighter at the top, whereas the same image rotated by 180° (left panel) looks concave. Have we created an illusion by juxtaposing them?

Others have proposed that the system considers statistical probabilities by defaulting to contextually appropriate, high-frequency responses (Reason 1992) or by applying the Bayes-theorem (e.g., Knill & Richards 1996; Kersten et al. 2004), or predictive processing (Clark this collection; Hohwy this collection) Here we are not concerned with the exact nature of how the construction is accomplished. Note, however, that all the solutions that have been proposed abound with cognitive ingredients. The process of constructing a 3D object from the 2D retinal input is usually thought to draw on memory and on some sort of inferencing, albeit unconsciously. The next step to arriving at meaningful percepts on the basis of the 3D object—which is just as essential in perception—involves even more cognitive elements, be they unconscious or amenable to consciousness.

Here I would like to include a brief aside, which may seem obvious to the psychologist but not so obvious to the philosopher. Perceiving cannot be dissected successfully into a sensational part and a judgmental part when we are dealing with the everyday perception of meaningful objects. Perceiving is always judgmental when we see a stick or a bird, or when it comes to seeing that we can pick up the stick and that it falls down when we release it. In other words, pure sensations may be possible introspectively —sensing red, sensing heat etc.—but they are no longer possible in everyday object perception, that is a separation of sensation and judgment is not ecologically valid. Take, for instance, the falling object as given in phenomenal perception. In the sub-field of experimental psychology called "intuitive physics", investigators have doctored physical events to contradict Newtonian physics and presented visual animations to novice or expert observers. Many of the latter do not see anything wrong with objects falling straight down when released, as opposed to following the proper parabola that they should (see section 1.3.1 on so-called cognitive illusions). This perception is reflected in motor action—people release the object in the wrong place when trying to hit a container; this perception arises in toddlers unable to reflect upon the event, and it persists after formal physics training in cases where observers have to make quick decisions. Thus, a separation into a sensation and perceptual judgment is not meaningful here. Perception of (everyday) objects and events necessarily includes a judgmental aspect, which may or may not enter consciousness.

Now, we are concerned with the question of whether the errors that arise during the perceptual process can be used to gauge where the visual system fails to capture the 3D world. We will argue that this is not the case. Research focusing on so-called optical illusions is particularly ill-suited to gain insight into how the visual system solves the UP. Illusions typically arise when errors are rather small, thus the presence or magnitude of an illusion is no predictor of the size of the UP. By and large, perceptual error is rather small when it comes to simple object properties, such as size, distance, direction of motion, etc. Errors become much larger, more interesting, and potentially dangerous when it comes to relational properties, such as seeing if an object can be lifted or if I will slip and fall when treading on a given surface. The case studies below will show that in the context of relational properties we make errors but we do not experience illusions.

1.2 The Luther illusion

Please take a close look at this painting of Martin Luther. You have certainly seen pictures of the great protestant reformer before. Does anything about this painting strike you as strange?

Figure 3: Martin Luther as painted by Lukas Cranach the Elder (1529), Hessisches Landesmuseum Darmstadt.

You may have found that he looks well nourished, as is appropriate for a monk whose enjoyment of worldly pleasures is well documented. However, I am sure you did not notice the illusion. Well, I have photoshopped the photograph and made it 15% wider than it should be. There is a discrepancy between the painting (or veridical photograph thereof) and the picture presented in Figure 3. Such discrepancies are typically considered to be the essence of illusion. For instance, Martinez-Conde & Macknik (2010, p. 4) define an illusion as "the dissociation between the physical reality and the subjective perception of an object or event". The physical reality of the picture is distorted by 15%, but your perception was that of a correct rendition of a famous painting. Now let us add another twist to the Luther illusion (Figure 4).

Figure 4: Martin Luther right side up and upside down.

Have I taken the original photograph or have I turned around the 15% wider version? Surely, Luther looks to be slimmer in the panel on the right. If you turn the page upside down, you will see that both panels show the same picture that is 15% wider than the original. Let us assume that the inversion effect—also named fat-face-thin-illusion by Peter Thompson (Thompson & Wilson 2012)—is exactly 15 % in magnitude. Has the illusion that I introduced initially been nullified by the inversion?

The fictitious Luther illusion is meant to make the point that the mere discrepancy between physical reality and a percept should not be conceived of as illusory. It may not even be reasonable to conceive of it as an error. The stretched image may be a better representation of what we know about Luther than the "correct" picture. For instance, the picture may typically be viewed from an inappropriate vantage point that could make the stretched version more veridical even when compared to the actual Luther, were he teleported into our time. Take Figure 5. I have stretched Luther by another 50%. Now he seems a bit distorted, but not to an extent that would prevent us from recognizing him or from enjoying the picture. There is a fundamental property that needs to be added for something to be considered an illusion. I contend that this is a dual simultaneous percept that tells us that what we see is so and not so at the same time (for a detailed defence of this position see Hecht 2013). For an illusion[1] to be called thus, it has to be manifest immediately and perceptually. Calling something an illusion is only meaningful if it refers to a discrepancy that we can see. It is not meaningful if it refers to some error that we have to infer.

Figure 5: Martin Luther stretched by another 50%.

Take for instance the often-cited stick in the water that looks bent. The static image presented in Figure 6 is not an illusion. We see a bent stick; note that its shadow is bent as well, and without recourse to our experience of refraction that occurs where two media adjoin, we would not know if the stick were actually bent or if some effect of optics had created the percept. However, the moment we move the stick up and down we see the illusion$_m$. We see the stick being bent and being straight at the same time. The illusion becomes manifest. That is, the discrepancy if not contradiction between the two percepts (here the straight and the bent stick) is available in our working memory, we become aware of it, often without being able to resolve which of the two discrepant percepts is closer to reality. In the case of the stick, the location of the bending at water level reveals that

1 Note that I will differentiate between illusion$_d$ (being the old notion of discrepancy between object and percept) and illusion$_m$ (the manifest illusion that is perceived rather than inferred with the help of physics text books). I will only refer to illusion$_m$ as illusion, whereas I will refer to illusion$_d$ as mere error or discrepancy. See also the related distinction between phenomenally opaque and phenomenally transparent illusions (e.g., Metzinger 2003a, 2003b). My distinction between illusion$_d$ and illusion$_m$ is meant to be merely perceptual.

the stick is really straight; however, in most cases the illusion$_m$ remains unresolved, as for example in the case of the Ebbinghaus illusion.

Figure 6: Is the stick bent?

1.3 Thesis: Illusions$_m$ are not evidence of error but rather unmasking of error

It would make no sense to call the circles in Figure 7 an illusion$_m$, even if a researcher could show with a large dataset that the inner circle is reproduced 2% bigger than it was on the picture. However, as soon as we allow for a direct comparison and put a ruler to the center circles in Figure 8, the illusion$_m$ arises (see Wundt 1898; an interactive demonstration of the Ebbinghaus illusion can be found at http://michaelbach.de/ot/cog-Ebbinghaus/index-de.html).

Illusions$_m$ are perceptually immediate but they appear to require some form of comparison and judgment, which supports the argument that phenomenal perception cannot be divided into a merely sensational core and a cognitive elaboration. For instance, in the case of a Necker cube or a bi-stable apparent motion quartet, the illusion$_m$ can become manifest by a mere deliberate shift of attention.

Given the severity of the UP, we should not be fascinated by the existence of error (illusions$_d$), but should instead be fascinated by the fact that our perceptions are pretty much on target most of the time. It is truly amazing that among the enormous range of possible interpretations of the retinal image, we usually pick the appropriate one. Illusions$_m$ are rare special cases of ubiquitous small errors that become manifest because of some coincidence or another. Note that this assessment does not only apply to visual perception but also to other sensory modalities in which sensory information has to be interpreted and integrated. For instance, the cutaneous rabbit illusion$_m$ arises when adjacent locations on the skin of our arm are stimulated in sequence. We experience one coherent motion (a rabbit moving along our arm) rather than a sequence of unrelated taps. This "inference" can be explained by probabilistic reasoning (Goldreich 2007) and may be considered the tactile analogue of apparent motion: just as we cannot perceptually distinguish a sequence of static stimuli from real motion in the movie theater. As a matter of fact, the pauses between the intermittent frames of the movie are indispensable for motion pictures to look smooth and continuous.

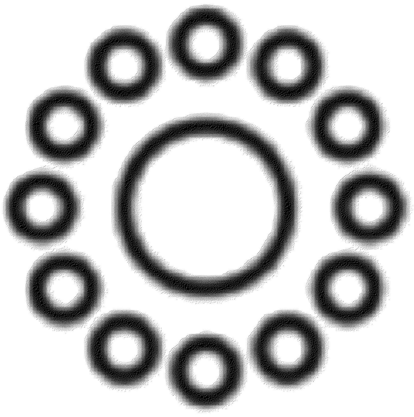

Figure 7: Is the circle in the middle perceived to be bigger than it really is? Possibly an illusion$_d$.

Gestalt psychologists have described the constructive process by which meaningful objects emerge from the various elements in our sensory core (see e.g., Max Wertheimer 1912 for the case of apparent motion). For good reason, they have avoided the term illusion, and introduced the term emergent property for the phenomenal result of the (unconscious) process of perceptual organization. It would violate our everyday experience to call something we see an illusion just because we know a little bit about the underlying physics. Just because we know that our continuous motion percept is derived from a sequence of discrete images, this does not make the percept an illusion (neither illusion$_m$ nor llusion$_d$).[2] By the same token, knowing that light is a wave (or a stream of photons) does not make objects in the world illusory. In fact, a discrepancy between what is really there and what we perceive is the norm, not the exception. Given my conceptual distinction, I will show how the perceptual system deals with the ubiquitous discrepancy, with the normal case of illusion$_d$. The relatively rare cases illusions$_m$ arise a by-product of this process. For something to deserve the name illusion, this discrepancy has to become manifest. The Ebbinghaus illusion only turns into an illusion$_m$ when we perceive a conflict, when the inner circles are seen (or inferred) to be equal in size and they look different in size at the same time. Thus, it is not the ubiquitous presence of error that makes an illusion$_m$ but the rather unusual case where this error is unmasked by a perceptual comparison process.

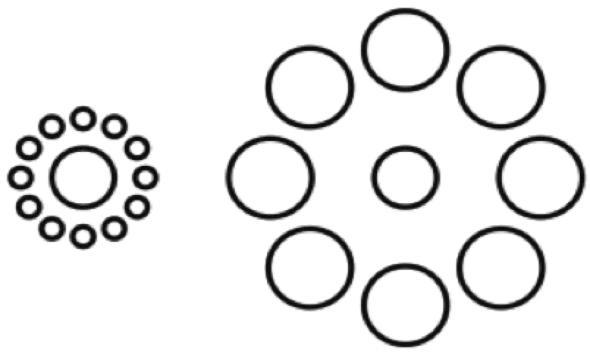

Figure 8: Is the circle surrounded by smaller circles perceived to be bigger than it really is, or is the center circle on the right perceived to be too small? This is the famous Titchener illusion$_m$ that was invented by Hermann Ebbinghaus and first reported by Wilhelm Wundt (1898).

2 Note, that a discrepancy between stimulus and percept is necessary but not sufficient for an illusion$_m$. Thus, all illusions require an illusion$_d$ but will only become illusions$_m$ in some cases. My distinction is capable of sorting out illusions as relevant to perceptual psychology, it does, however, not speak to the question of how we can describe the physical stimulus in the first place, i.e., the grand illusion argument (see http://www.imprint.co.uk/books/noe.html).

1.3.1 A note on so-called cognitive illusions$_d$

In our everyday perception, once we consider that objects are often in motion and carry meaning at the perceptual level (see Gibson's concept of affordance, e.g., 1979) the UP is exacerbated but not changed. I argue that the nature of perceptual error is akin to cognitive error when it comes to the more complex and meaning-laden percepts of everyday perception, as opposed to line drawings that are typically referred to in the context of illusions$_m$. Just as with perceptual errors, cognitive errors often do not become manifest. However, if they do become manifest, they can typically be corrected with much greater ease than can perceptual illusions$_m$, which may well be the distinguishing feature between perceptual and cognitive error. Cognitive errors become noticeable more indirectly by recurring to a short-term memory of a dissenting fact or by reasoning—which is often faulty by itself. The literature about cognitive error is enormous. To give one classical example, we have trouble with simple syllogistic reasoning, in particular if negations are used. Wason's famous selection task (Wason & Johnson-Laird 1972) shows how limited our abilities are (Figure 9). Imagine you have four envelopes in front of you. You are to test the statement "if there is sender information on the back side then there is a stamp on the front". Which of the 4 envelopes do you have to turn over? Do not turn over any envelope unnecessarily.

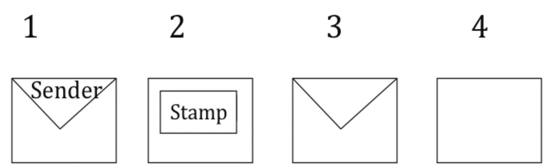

Figure 9: Which envelopes do you have to turn to test the statement "If there is sender information on the back side then there is a stamp on the front"?

Well—it is easy to see that envelope 1 has to be turned (modus ponens), but then it gets harder. Many observers think that envelope 2 needs to be turned. However, this is not the case. Only 4 has to be turned in addition to 1.

A sender on its back would violate the rule (modus tollens). The majority of college students fail to solve this problem, but as soon as the context is changed, all mistakes can be eliminated. In the context of screening for drinking underage, all observers perform accurately (see Figure 10). Here again 1 and 4 need to be "turned over". Only by thinking the problem through or by noticing that the problem structure is identical to the envelope scenario and the wine drinking scenario does the error become manifest. We may or may not want to call it a cognitive illusion. This term is not widely used for such mistakes or fallacies, with the exception of Gerd Gigerenzer and his research group (see e.g., Hertwig & Ortmann 2005). However, even if we call these mistakes cognitive illusions, they are different in nature from perceptual illusions$_m$ (which typically contain a judgmental aspect). We do not readily notice cognitive illusions. Although the distinction between perception and cognition has outlived itself (and cannot me made with clarity to begin with, see above), for practical convenience, I will continue to use the terms to emphasize cases where deliberate thought processes enter the equation. We happily live with many a fallacy without ever noticing. Millions went through their lives believing in impetus theory and seeing the sun circle around the earth, let alone holding seemingly absurd beliefs about the shape of our planet.

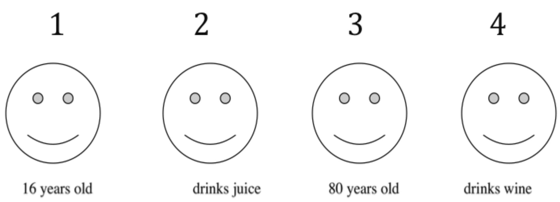

Figure 10: Whom do you have to query about age or beverage type to test if "Only adults have alcoholic beverages in their glass"? It is obvious that the juice drinker and the elderly person need not be queried.

Errors only turn into illusions$_m$ when we become aware of them and at the same time cannot correct the error (easily). Just try to see the earth rotate rather than see the sun rise. It is impossible. We continue to see the sun rise above a stable horizon, never the other way around. And we continue to misjudge implication rules or widen the grasp of our fingers a tad more when reaching for an Ebbinghaus stimulus even if we know about the illusion (see Franz et al. 2000). Other errors can only be spotted when large data samples are collected and analyzed statistically. For instance, to expert golfers, the putting hole on the green looks larger than it does to novices (Witt et al. 2008; Proffitt & Linkenauger 2013). They will never become aware of this fact, although the fine-grained scaling of perception as function of skill might be functional during skill acquisition. Spectacular as they may be, such errors of which we are unaware should not be called illusions$_m$ because almost all our perceptions and cognitions contain some degree of error. We may believe that a rolling ball comes to a stop because it has used up its impetus, or we may hold that we should aim where we want a moving ball to go rather than using the appropriate vector addition to determine where to aim. As long as our action results do not force us to reconsider, our convictions will remain unchanged. One could say that we have a model of the world, or its workings, that suffices for our purposes.

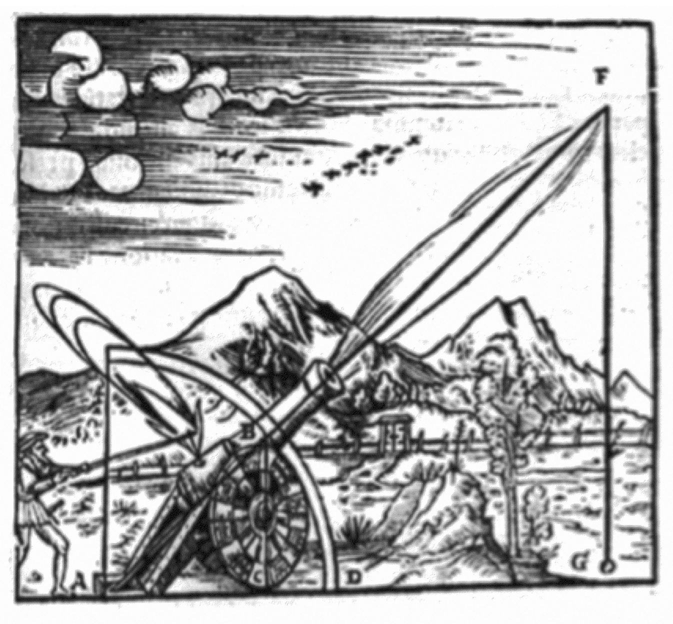

Figure 11: Technical illustration explaining the trajectory of a cannon projectile by Daniel Santbech (1561): Problematum Astronomicorum, Basel.

Why are so many researchers willing to call a small manifest discrepancy between two percepts of the same object an illusion, while gross deviations of perception or conception from physical reality are not deemed to deserve the same name? Take the straight-down belief (not illusion). Many observers take an object that is being released from a moving carrier to fall straight down rather than in a parabola (McCloskey et al. 1983). Figure 11 illustrates this belief as it was state-of-the-art physics knowledge from Aristotle through the Middle Ages. It persists today in cognition and perception. Even when impossible events of straight down trajectories are shown in animated movies, to some observers they look better than do the correct parabolas (Kaiser et al. 1992).

Note that there was a discussion at the time whether or not the transition from the upward impetus to the downward impetus was immediate or if a third circular impetus inserted itself, such that there were be two trajectory changes. The intermediary could only be thought of as linear or as a circular arc—anything else would have been too far from divine perfection. Presumably, the more principled physicists before Galileo favored the simple transition. Others, such as Aristotle himself, presumably preferred the interstition of the circular arc, as it would reconcile trajectory observation with the physics of the time. The pre-Newtonian thinking about projectile motion nicely illustrates that we see the world as in accord with our actions. To the medieval cannoneer, what he saw and understood about projectiles was sufficiently accurate, given the variance introduced by the inconsistent quality of the gunpowder and the fluctuation in the weight of cannon balls at the time.

Thus, we have argued that visual illusions$_m$, just as cognitive illusions$_m$, have to become manifest to be called such. They are a special and rare case in which the discrepancy between a percept and what an ideal observer should have seen instead is noticed. Normally this discrepancy goes unnoticed. We will now take a look at why it goes unnoticed and argue that an illusion$_d$ will only alter perception if it interferes seriously with our action requirements. As the latter vary among people, illusions$_d$ can be private and may be very far from the truth—as, for instance, in the context of projectile motion (see Hecht & Bertamini 2000). The private aspect of perception is to be taken as unconscious in the sense of Helmholtz. For instance, we do not only think that a baseball thrown toward a catcher will accelerate after it has left the thrower's hand (which may even be incompatible with impetus theory), but doctored visual scenes in which the ball does accelerate are judged as perfectly natural looking. This amounts to the perceptual analogue of what Herbert Simon (1990) has called satisficing in the domain of reasoning and intuitive judgment. The visual system searches until it has found a solution that is satisfactory, regardless of how far away it is from a veridical representation of the world.

To conclude this section, we believe that perception of objects, be it the stick in the water or a falling brick, is a solution to the underspecification problem. Perception is always fraught with error in the sense of a discrepancy between the percept and the underlying physics. This error only becomes manifest when a simple perceptual judgment or comparison reveals a contradiction. In all other cases the error goes unnoticed. Two such cases will now be described at length to make the point that perceptual illusion$_d$ is the rule rather than the exception.

2 Two case studies or how we deal with error

The study of geometric illusions or overestimation of slope, distance, and size as a function of situatedness misleads us into believing that perception normally reveals the true state of affairs. The finding that golf holes look slightly bigger to experts as compared to inexperienced golfers is spectacular because and only if we assume that perception is normally veridical. This is, however, not the case. Normally, our grasp of the physical world is rather limited. I present novel data from two everyday domains that differ from the standard examples of intuitive physics in a crucial way. They deal with the understanding (first case study) and the perception (second case study) of relational properties, rather than with more straight-forward perception of simple properties.

Seeing the color of an object or its size, predicting its motion trajectory, etc., refer to simple properties. Most everyday activities, however, involve relational properties. We need to see and predict how we might interact with objects in the world. This interaction depends on our own makeup, on the object's properties, and on the relation between the two. For instance, to judge whether a slope might be too slippery for us to walk on depends on the quality of the soles of my shoes, the surface texture of the slope, and also on their interaction. A polished hardwood ramp may be slippery if I am wearing shoes with leather soles, but it may be very sticky if I am barefoot.

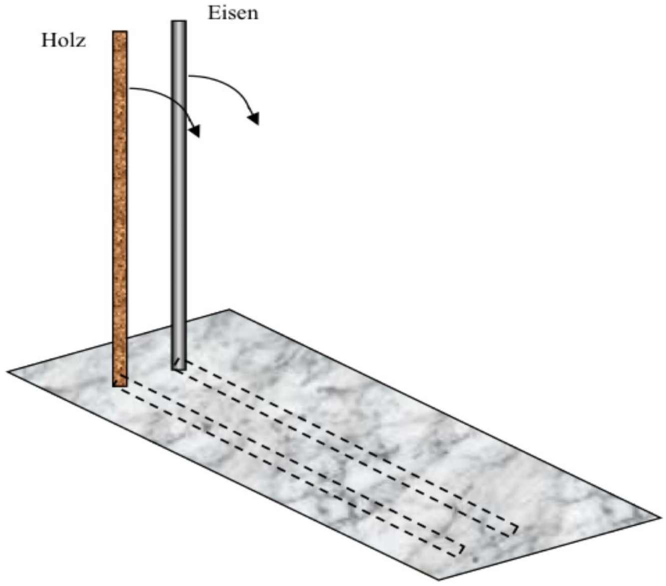

Figure 12: Task 1: The rod on the left is light, it is made of wood; the rod on the right is heavier because it is made of iron. If they begin to tip over at the same moment in time, which one will fall faster?

The two case studies that follow are intended to illustrate in detail how limited our understanding of relational properties is in general, and to show that we have to make decisions in the face of poor perception that may have serious consequences.

2.1 Case study: Balancing as a relational property

Before you read on, please take a minute to solve six questions about the depicted falling rods. Solutions will be provided later. Note that in tasks 1 through 3 (see Figure 12, 13, 14), the scenario is as follows. Two rods are held upright, but they are very slightly tipped to one side (by exactly equal amounts), such that they will fall once released. They are released at exactly the same moment. Which one will hit the ground sooner? In tasks 4–6, you are to judge the ease of balancing such a rod on the tip of your index finger.

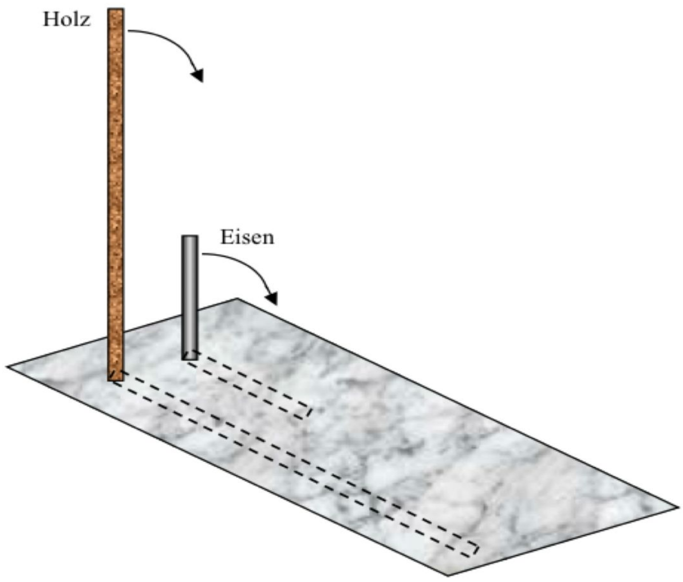

Figure 13: In Task 2 the rods are equally heavy but have different lengths. The left rod is made of wood; the rod on the right is shorter but has the same weight as it is made of steel. Which one will fall faster?

Task 4 asks about the same rods as in Task 1, but the question is whether the wooden or the steel rod would be easier to balance on the tip of your index finger.

Task 5 asks whether the short steel rod or the longer wooden rod of equal weight would be easier to balance on the index finger. And finally, Task 6 asks whether a weight attached to a given rod would make it easier to balance, and if so, where it best be attached (top, center, bottom). In a large survey, we tested the intuitive knowledge of a large number of college students about these tasks. Note that we tested such that each subject only had to solve one of the six tasks.

2.1.1 Methods detail

180 college students (123 women, 57 men, age $M = 24.9$ $SD = 5.9$, ranging from 18 to 53

years) volunteered to participate in the survey. We used a paper-and-pencil test to investigate the subjects' knowledge and to obtain their estimates about which objects would be easier to balance. The six tasks were explained carefully and illustrated with drawings similar to those shown in Figure 12, 13 and 14.

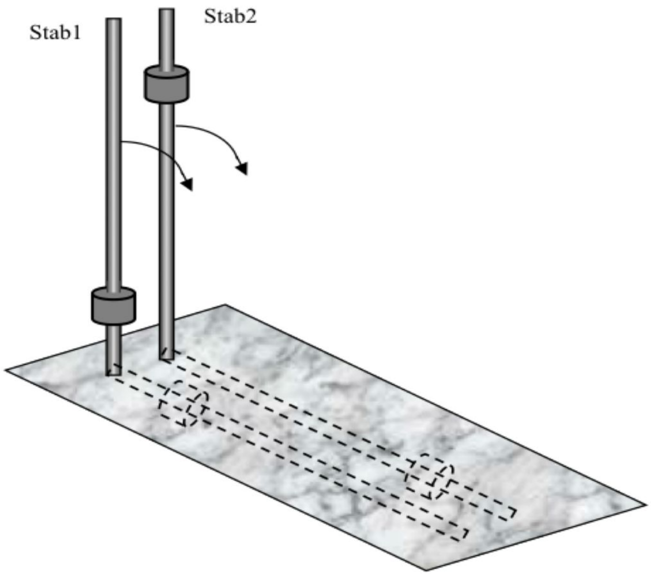

Figure 14: In Task 3, the two rods are identical in material, length, and weight. An additional weight is attached either at the bottom or at the top. Which rod will fall faster?

Each task was presented to 30 students. Tasks 1–3 were used to test intuitive knowledge without referring or alluding to the act of balancing. Merely the process of falling from an almost upright position to a horizontal position had to be judged. In the first task (Figure 12), subjects saw two rods of equal length (1m) but of different material and weight. The wooden rod was said to weigh 40g, the steel rod 400g. The accompanying information text indicated that both rods were slightly tipped over at the exact same time, for instance by a minimal breeze. The wooden rod was to take exactly 1.5 seconds to fall from its upright position to the horizontal. We had tested the falling speed of such rods and measured it to be approximately 1.5s. The subjects were asked to estimate the fall-duration of the steel rod. The second (Figure 13) task showed two rods of equal mass (40g) but different length (rod 1 = 100cm, rod 2 = 36cm). The information text was the same as in Task 1. The third task (Figure 14) showed two rods of equal length (1m) and weight (220g). However, an additional small object (220g) was placed respectively toward the top or the bottom of the rod (rod 1 = 10cm from the bottom, rod 2 = 90cm from the bottom). The accompanying information text indicated that both rods would be tipped over by a minimal breeze and that it took rod 1 exactly 1.5 seconds to fall to a horizontal position. Subjects were to estimate the fall-duration of rod 2.

Tasks 4–6 used the same rods but the questions about them were couched in the context of balancing. This should evoke experiences that subjects may have made when balancing or hefting objects. Thus, rather than asking which rod would fall quicker, we asked which would be easier to balance.

The fourth task showed the same two rods of equal length (1m) but different weights (wooden rod = 40g, heavy steel rod = 400g) that had been used for Task 1 (Figure 12). The subjects were asked to indicate which rod they thought they could better balance on the tip of one finger, typically the index finger. The possible answers ranged from 1 ("rod 1 much better than rod 2") to 7 ("rod 2 much better than rod 1"). The fifth task (Figure 13) showed two rods of equal weight (40g) but different length (rod 1 = 100cm, rod 2 = 36cm). Again, the subjects were asked to indicate which rod they could better balance with one finger. Task 6 showed one rod (length = 1m, weight = 220g). Subjects had to indicate the position that they would place an additional small object (mass = 220g) to get optimal balancing characteristics (from 10cm = bottom to 100cm = top). It was made clear that the weight would not come into contact with the balancing hand even when it was placed at the bottom.

2.1.2 Results

People who cannot draw on formal physics training to answer the six tasks have a rather poor intuitive understanding of falling rods. Neglecting air resistance, the rate of falling is determined by how high the center of gravity (barycenter) is above the ground. The rod's mass is irrelevant. Thus, rods of equal length (mass distribution is assumed to be uniform) fall at the same rate, but the shorter rod falls quicker than its longer counterpart. By the same token, a weight attached to the tip of the rod should cause it to fall more slowly because it moves the barycenter closer to the tip.

In general, the subjects estimated their knowledge in the natural sciences to be moderate when asked to judge it on a six-point scale ranging from very poor (1) to very good (6). Mathematics knowledge ($M = 3.62$, $SD = 1.13$) was judged better ($t(179) = 11.98$, $p < .001$) than physics knowledge ($M = 2.56$, $SD = 1.26$). The men estimated their knowledge somewhat higher than did the women, for physics ($t(178) = 8.8$, $p < .001$) and mathematics ($t(178) = 2.34$, $p < .05$).

Task 1: In reality, both rods fall with the same speed, as Galileo Galilei showed in 1590 with the help of several experiments about free fall (e.g., Hermann 1981). The falling speed is independent of their mass as long as air resistance is negligible. Thus, 1.5 seconds was the right answer. 40% of the test subjects answered correctly. 43.3% estimated that the heavier rod would fall faster, while 16.7% estimated that it would fall more slowly.

Task 2: Because of the lower barycenter the shorter rod falls faster and its fall-duration is briefer than 1.5 seconds. 46.7% of the test subjects indicated this. 44.3% thought that the fall-duration would be the same and 10% estimated that the shorter rod would fall more slowly.

Task 3: Because of the higher barycenter, the second rod falls more slowly. Therefore, its fall-duration is longer than 1.5 seconds. Only 20% of the subjects chose the right answer. 50% estimated that the rod with the higher barycenter would fall faster and 30% estimated that it would fall at the same rate.

There is a direct link between the fall-duration of an object and the ability to balance this object. The longer the fall-duration, the more time there should be to move the balancing finger right underneath the barycenter, and hence the easier to balance (a moderate weight assumed). We confirmed this hypothesis empirically in several experiments where subjects actually had to balance different rods to which weights were attached at different heights. Thus, we can predict the ability to balance different objects by comparing their fall-duration.

Task 4: Here, the rods (same length, different weight) had the same fall-duration—so the ability to balance them can be assumed to be the same, too. This was recognized by only 3.3% of the test subjects, while 73% favored the heavier rod, and 23.3% the lighter one.

Task 5 (two rods, same weight, different length): Because of the longer fall-duration the longer rod is easier to balance. This was assumed by 56.7% of the subjects. 20% estimated both rods to be equal and 23.3% thought the shorter one would be easier to balance.

Task 6 (additional weight): The higher the barycenter the longer the fall-duration—and with it the ease of balancing. Therefore, the additional object should be placed at the top of the rod. This was indicated by 33.3% of the test subjects. The majority of 43.3% chose the bottom for placing the object, and 23.3 % chose positions between bottom and top.

In sum, the intuitive knowledge about the fall of different objects is rather spotty. About half of the subjects knew that fall-duration is independent of mass (Task 1) and that shorter objects fall faster (Task 2), only 20% realized that the position of the barycenter is relevant and that the fall-duration increases when the barycenter is shifted to the upper end of the rod (Task 3). This is remarkable because on a daily basis we handle objects whose barycenter differs from the geometrical center, for instance a filled vs. an empty soup ladle, top-heavy tennis rackets, etc.

Asking directly about the act of balancing did not reveal superior understanding. When asked about their ability to balance objects, people do know that longer objects are easier to balance than shorter ones, but they do not seem to realize that the mass of the object is irrelevant (Tasks 4 and 5). In other words, although a majority of our subjects was able to recognize that mass is irrelevant for fall duration, they failed to see the irrelevance of mass in the relational balancing task. The involvement of the own motor action appears to have made the judgment task more difficult. The important role of the position of the barycenter (i.e., mass distribution, Task 6) went equally unnoticed in the falling and the balancing tasks. In general, knowledge about balancing properties and the underlying physical principles can be described as rather moderate. Do experts have a superior understanding of these principles?

2.2 Extending the case study: Comparing physics experts with non-experts

As all subjects had judged their physics knowledge to be rather limited, we chose to test a group with formal physics training on the balancing questions. We also tested a social science control group and added two new tasks. Tasks 1–3 were dropped from the study, while Tasks 4–6 were included. To test for a specific heuristic, namely that heavy objects are harder to balance, the following two tasks were added:

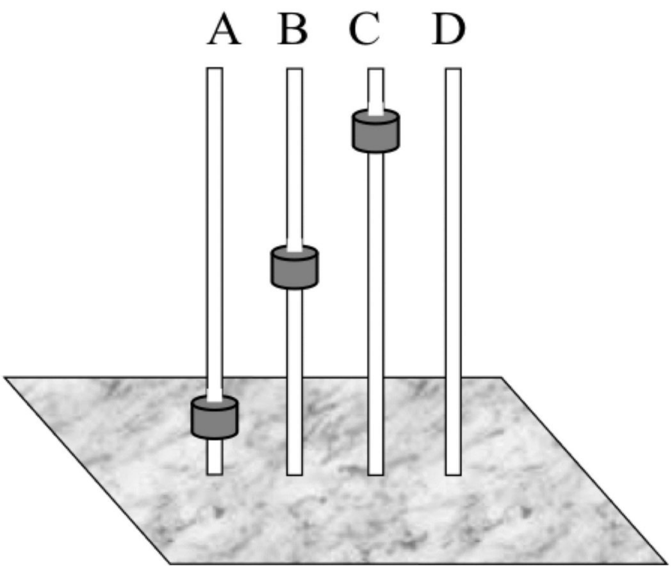

Figure 15: In Task 8, the four rods labeled A–D should be sorted according to the difficulty of balancing them. The correct order is C–B–D–A or C–D–B–A.

Task 7: The question "Does a weight help and if so, where would you place it?" was posed with respect to the much lighter wooden rod (m = 40g). Thus, Task 6 was replicated with a lighter rod. Finally, a more fine-graded question was added to assess by how much expert knowledge would be superior to normal knowledge, if at all:

Task 8: The eighth task showed four rods of the same material (steel, length 90cm). On three of them, a weight was attached at different positions (as shown in Figure 15). The subjects had to order them according to which would be easiest to balance on the tip of one finger. Note that the height of the barycenter matters. It is equally located in the center of rods B and D.

2.2.1 Methods detail

Participants: 84 college students, mainly of Psychology (69 women, 15 men, age ranging from 19 to 66 years) and 113 college students of Physics, Mathematics, and Chemistry (41 women, 72 men, age ranging from 18 to 27 years) were tested. The students of mathematics, physics, and chemistry estimated their knowledge in mathematics (M = 2.65, SD = 1.02) and physics (M = 2.68, SD = 1.07) to be moderate. The men estimated their knowledge of physics to be higher than did the women ($t(111)$ = -4.34, p < .001). No difference was found for self-assessed maths skills ($t(111)$ = -.22, p=.83).

A paper-and-pencil test was used to investigate the assumptions subjects held about the effect of various object properties on how easily the respective rods could be balanced. The test booklet included eight tasks: one per page. Each task consisted of a hypothetical scenario illustrated by a drawing. Different pseudo-random orders of the eight tasks were executed by all students. Tasks that built upon one another were kept in their logical order. Once a given task was finished, the page had to be turned. It was not permitted to go back to a previous page. Depending on the task, subjects had to make a binary choice (pick one or answer yes or no) or they had to grade their answers on a seven-point scale, according to how sure they were that one alternative would win over the other (certain win, very likely, somewhat likely, equal chance, somewhat unlikely, very unlikely, certain loss).

2.2.2 Results and discussion

Task 4 (equal length, different weight of the rods)**:** Only 3.6 % of all social science students produced the correct solution and stated that the wooden and the steel rod would be equally hard to balance. Half of them thought that the steel rod would be easier to balance, and the remaining subjects chose the wooden rod. This corresponds well to the results obtained with the first large student sample. The physics students, in contrast, performed better albeit nowhere near perfection. 22% of them chose the correct answer. 21% thought the wooden rod would be easier to balance, and 57% thought the steel rod would be easier to balance. Thus, social scientists equally chose one or the other whereas physicists preferred the metal rod, and at most one fifth of them knew the correct answer (provided they were not just guessing better than the social science students).

Task 5 (equal weight, different length)**:** Half of the social science students (53%) correctly thought that the longer rod would be easier to balance, and less than 2% thought that length did not matter. The physics students did noticeably better: 76% chose the longer rod, and only 20% thought the shorter rod would be easier to balance. 4% thought it would be the same with both rods.

In **Task 6** (attach weight to steel rod): 60.7% of the social scientists thought that a weight would make it easier. When asked to place the weight, only 9.5% put it in the top third (for analysis purposes the rod was divided in three equal parts), and 44% placed it at the bottom third. Physics students fared a little better. A mere 44 % thought that a weight would improve balancing, but those who did correctly placed the weight at the top (40% of all physics students).

Task 7 (attach weight to light wooden rod): Not surprisingly, performance was very similar to Task 6 (r= 0.76). If anything, the rod's being lighter improved performance. 77.4% of the social scientists thought that a weight would make it easier. When asked to place the weight, only 19% put it in the top third. 45.2% put the weight in the bottom section, and the remaining students placed it in the middle section of the rod. Physics students fared a little better. 81% thought that a weight would improve balancing. However, the correct placement at the top was made by only 40%. Thus, in light of the results from Task 6, it seems that those who knew the correct answer were unimpressed by the weight of the rod. However, among those experts who merely guessed and suspected that weight would make a difference, they guessed so more often when the rod was lighter—increasing the salience of the weight.

Task 8 (order the rods)**:** Social science students: According to the reasoning that a greater moment of inertia should facilitate balancing (note that this will not hold for much heavier rods), the correct order is C, B = D, A. Not a single subject produced this answer. 16.7% chose the order A, B, D, C; another 16.7% chose A, D, B, C. Only one subject considered a tie, albeit with a wrong ordering (B, D, A=C).

Physics students: Notably, 6% of the subjects did give the correct answer of CBDA or CDBA. 94% of the subjects answered incorrectly. Thus, the physics students were somewhat more knowledgeable than the social science students.

In sum, the errors we make in perceiving the balancing properties of simple objects are large. The important variable of mass distribution is ignored entirely. We plainly do not see how an object is best balanced until we try it out, even though we balance objects on a daily basis. Most if not all observers are unable to correctly imagine or remember past balancing acts. Formal physics training has surprisingly little effect on the paper-and-pencil task for assessing falling and balancing of rods. Note that the classical mechanics knowledge that would help solve the problem should have been held by all natural science students involved in the study. The fact that their answers were only slightly superior to novice intuitions is stunning. Why is the textbook knowledge of classical mechanics so frail that it has not been internalized, such as to inform our intuitive judgments or at least facilitate our textbook learning?

Throughout evolution we had to handle and wield objects by balancing them. One might argue that such knowledge is not available to the ventral processing stream (see Milner & Goodale 2008). However, in further tests we confirmed that performance in our tasks did not improve when we let subjects wield a rod before filling out the questionnaire. Even though observers are able to feel how long a stick is when wielding it while being blindfolded (see Turvey & Carello 1995), they are unable to exploit the available perceptual cues that inform them about the balancing properties of an object. Thus, although we know shockingly little about balancing, it seems to be sufficient to guide our daily actions. We correctly see longer sticks as being easier to balance, but we fail to see the importance of mass distribution. Even when educated by formal physics training, our performance becomes only slightly more sophisticated. The gap between percept and reality closes merely by a small amount. It appears that the visual systems of different observers adopt different private models that often include rod length but not mass distribution.

2.3 The second case study: Visual cues to friction

Let us now look at another relational property that may have more serious consequences for our health: friction. If we misbalance an object, we may break it, but if we misjudge the slipperiness of the surface we walk on, we may get hurt. We need to avoid accidents on slippery ground and we have to estimate the force we need to apply to hold an object. Importantly, we often cannot wait for haptic cues to make this information available, but typically we have to make the underlying judgment of slipperiness on the basis of visual cues. The mere look of a wet slope may be all we have to guide our decision to tread forcefully or to hold on to a hand-rail and walk gingerly. The human ability to make such visual assessments of slipperiness is not well explored. We hold that this is because friction is not a simple surface property but rather a relational property, which can only be determined by relative characteristics of two surfaces. In other words, the fact that a surface is rough does not imply high friction, and the fact that a surface is smooth does not imply that it is slippery. Plastic for instance, can be very sticky on human skin but very slippery on wool or felt.

In what follows, we provide an overview of friction perception and briefly introduce venues to visual and haptic roughness perception. Then we report two experiments that were conducted to assess visual and haptic judgments of friction between surfaces.

2.3.1 Friction as a relational property vs. surface roughness

Some surfaces afford walking on whereas others do not. The information that allows the organism to make potentially critical decisions about where to tread or how strong a grip should be is based on a variety of perceptual dimensions (see e.g., Michaels & Carello 1981). Even when ample opportunity is given to haptically explore the surface, its felt roughness is not necessarily the same as the friction between the exploring hand and the surface, let alone the friction between the sole of the shoe and the surface. For instance, if our hand is moist we feel high friction when exploring a polished marble floor and at the same time we feel it to be very smooth. We may even perceive it as slippery—factoring in the effect of dry vs. moist hands.

Tactile competence regarding perceptual access to roughness of surfaces appears to be rather sophisticated (for a state-of-the-art review of haptic perception see Lederman & Klatzky 2009). In essence, haptic perception of surface roughness is better when the surface is explored dynamically as opposed to statically. Errors are generally rather small. More interestingly, several studies have demonstrated that cross-modal sensory information (e.g., vision and touch) can lead to better estimates of a texture's roughness (e.g., Heller 1982). Other research has also shown that different sensory modalities are weighted about equally when estimating the roughness of textures (Lederman & Abbott 1981; Lederman et al. 1986).

Even by mere visual inspection, observers are able to see how rough a surface is (Lederman & Klatzky 2009). Such findings may have tempted researchers to unduly reduce friction to surface roughness. For instance, in the ergonomics context of accident analysis, slipperiness of work surfaces is typically operationalized by surface roughness, with the implicit or explicit assumption that roughness is good enough an approximation of friction (see e.g., Chang 1999; Chang et al. 2001; Grönqvist et al. 2001). However, friction is a rather complicated property between surfaces, for one because it is subject to change with the amount of pressure one applies or with the speed at which the surfaces move relative to one another. And people appear to have some difficulty judging friction (Joh et al. 2007).

Let us consider the case of a square block of cement on a large wooden surface. The heavier the block, the higher the friction coefficient. And the rougher the surface of the block the higher the friction coefficient. Thus, friction is a function of the force applied to a given surface, of area, and of roughness. Children and adults seem to be able to perceptually appreciate some but not all of the above-mentioned three components of friction. This intuitive knowledge develops with age. Adults have some insight into the multiplicative relation between the weight of an object and its surface texture in cases where the object is pulled across a surface, whereas nine-year-old children seem to assume a simpler additive relationship (Frick et al. 2006).

Friction is defined by the interaction between two surfaces, and its estimation requires knowledge about how different surfaces can interact. Thus, the seemingly simple visual percept that we have of a surface as "slippery" is a rather complex physical relation that pertains between properties of the surface and the contact object. Physically, slipperiness is indicated by the friction coefficient between two surfaces, which is usually measured by placing an object on an adjustable ramp. As the steepness of the ramp increases, one determines the angle at which the object starts to slip (static friction) or when the object starts to move uniformly (kinetic friction).

We can haptically judge the roughness of surfaces, and we are also able—to some degree—to haptically judge the friction between surfaces. Grierson & Carnahan (2006) have shown that individuals can haptically perceive slipperiness; that is estimates were significantly correlated with the friction coefficients between an object's surface and skin. In their first experiment, they showed that tangential motion is required to judge the friction coefficient realistically. In a second experiment, they examined the force people applied to lift an object with a certain weight and surface structure. The applied force was often higher than necessary. Next to nothing is known about our ability to judge slipperiness based on visual information.

2.3.2 Slipperiness Experiment: Visual cues to friction of familiar surfaces

Vision has been shown to improve haptic judgments in endoscopic surgery. Within a simulated endoscopic environment, Perreault & Cao (2006) tested the effects of vision and friction on haptic perception by measuring for how long participants held on to the objects with the surgery tool. In a second experiment, participants had to compare the softness of pairs of simulated tissue. The experiments showed that visual and haptic feedback were equally important for the task. This suggests that visual cues can be exploited to judge slipperiness.

Presumably the main visual cue for predicting slipperiness or friction is shine (gloss, reflection, etc.) of a surface. Joh, Adolph, Campbell & Eppler (2006) explored which visual information can serve as a warning of low friction surfaces. They asked their participants which cues they use to identify slippery ground, and tested whether visual information is reliable for the judgment of slipperiness under different conditions (indoor and outdoor lightening). Walkers seem to rely on shine for selecting a safer, less slippery path, even though shine is not a very reliable visual cue for indicating slippery ground.

With two experiments we attempted to assess, in more general terms, the ability to perceive slipperiness. In our first experiment, we tried to find out to what extent visual and haptic information enables us to estimate friction between two surfaces and, in particular, how far visual cues in isolation decrease the ability to judge friction. In our second experiment, we manipulated the visual appearance of given surfaces to explore the effects of glossiness, contrast, and undulation on perceived friction.

Every day we encounter different types of surfaces with which we are in contact. In these situations we do not really think about how much force is to be exerted in order to create sufficient friction, be it between the fingers and the object we are grasping or between the sole of our shoes and the surface of the road we tread. Nonetheless, we rarely accidentally drop an object or slip on the road. Thus, we must have some degree of intuitive knowledge about the friction of surfaces. The experiment sought to find out, first, if this is really the case, and then which sensory information might guide our estimates of friction.

2.3.3 Methods detail

33 female and 31 male subjects between 18 and 52 years of age ($M = 25.3$; $SD = 6.6$) volunteered and were paid for participating in the study. All had normal or corrected to normal vision, and no one reported haptic impairments.

Ten different types of surfaces (see Figure 16) were glued onto separate thin quadratic tiles of wood with a size of 10 x 10cm. The surfaces were sheets of Teflon, pan liner, smooth and rough foam rubber, cloth, felt (soft and hard), and three different grades of sandpaper.

Two common reference surfaces were picked: human skin and smooth untreated wood. That is, the participants had to estimate the friction of the above ten surfaces with respect to one or the other of the two reference surfaces, skin or wood.

To measure the perceived friction, a ramp was used. Its slope could be adjusted to a steepness corresponding to the setting where the tile was judged to start sliding down. The ramp consisted of two wooden boards connected with a hinge. It was placed in front of the participant and could be continuously adjusted (see Figure 17). A measuring stick was attached to the top of the ramp such that the experimenter could easily record the height of the ramp while the participant saw only the unmarked side of the measuring stick. The height settings were then converted to slope angle, which in turn was used to determine the friction force acting between ramp and probe surface.

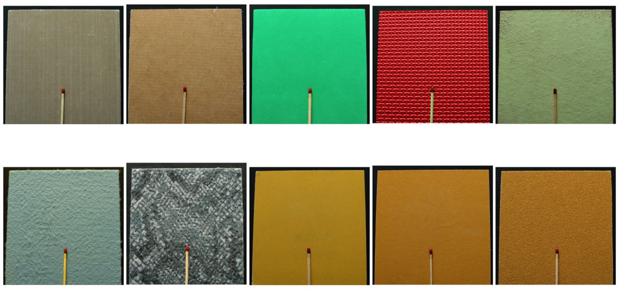

Figure 16: The ten materials used in the first experiment. Top row from left to right: Teflon, pan liner, smooth and rough foam rubber, cloth. Bottom row from left: felt (soft and hard), three different grades of sandpaper (320, 180, 40 in that order). All materials were mounted on identical square wooden tiles. The matchstick is shown to provide scale information, it was not there in the experiment.

The slope of the ramp used to estimate the friction of the different surfaces could be varied from 0 to 90 degrees. We computed coefficients of estimated static friction for the subsequent analyses using the following equation:

$\mu_H = \boldsymbol{F_R} \ / \ \boldsymbol{F_N}$ (friction coefficient = friction force / weight)

A 4 x 2 x 10 design was used, with one four-level between-subjects factor (Condition), and two within-subject factors, Reference Surface (two levels: skin and wood), and Surface Material (ten levels: Teflon, pan liner, smooth and rough foam rubber, cloth, felt (soft and hard), and three different grades of sandpaper).

The factor Condition consisted of different instructions for exploring the surface materials (see Table 1). In the haptic-visual condition, observers were asked to touch the surfaces and to visually inspect them. In the haptic condition, the surfaces were hidden in a box at all times and could only be explored haptically. In the visual condition, observers were not allowed to touch the surfaces but could inspect them visually. In the photo condition, finally, observers merely viewed photographs of all ten surfaces. The same photographs as depicted in Figure 16 were used, with the exception that the match was not present. The photographs were the same size as the actual tiles (10 x 10 cm).

Figure 17: The ramp used to measure the estimated friction coefficients produced by the participants. The ramp had to be adjusted to the angle at which the respective tile would just about start to slide. In the case of skin as reference surface, observers were told to imagine the ramp to be their torso or to be covered with skin.

Subjects were allowed to look at the respective reference surface (skin or wood) before making a set of judgments based on this reference surface. They were also allowed and encouraged to touch the reference surface regardless of the condition in which they were tested. That is, even the group that could only visually inspect the test surfaces had visual and haptic experience of the generic reference surface. The ramp itself was not to be touched in this phase of the experiment, in order to ensure that the groups did not differ in how they explored the ramp. To envision the friction of skin, subjects were instructed to touch the inner side of their forearm, and to envision the friction of wood, they had a piece of wood (the same wood also used for the ramp) lying in front of them that they could touch. Half of the participants started with wood as reference and then after a short pause used skin as reference. The other half started with skin and then judged wood. Within each block, the order of the surface tiles was randomized separately for each observer.

Table 1: The four test conditions under which separate groups of subjects were asked to explore the material surfaces.

I. Haptic-visual	The ten test surfaces were visible and could be touched without any restrictions.
II. Haptic	The surfaces were hidden in a box and could only be touched but not seen.
III. Visual	The subjects were only allowed to look at the surfaces.
IV. Photo	Photos of the surfaces were presented on a TFT-display, so only restricted visual information was available.

The procedure consisted of three parts. First, subjects had to estimate the friction of the ten materials, all presented successively and in random order. To do so, they had to adjust the slope of the ramp (see Figure 17). After inspecting the reference surface and the first tile, they had to set the ramp's slope to the point where they expected the particular surface to just start slipping on the ramp. The surface tiles were never physically placed on the ramp. Then the remaining nine tiles had to be judged in the same manner.

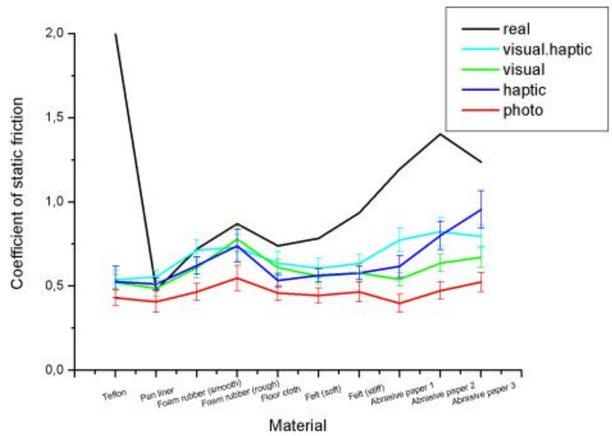

Figure 18: Actual and perceived coefficients of friction between **skin** and the respective materials. The solid black line corresponds to the actual angle of the slope at which the tile would indeed start to slide. The other lines represent subjective judgments averaged across all participants of each group respectively. Error bars indicate standard errors of the mean.

In the second part, a short questionnaire was given to the subjects. Finally, the procedure was repeated with the other reference surface. The order of which reference surface was chosen first was counterbalanced such that half the observers started with wood and the other half started with skin.

2.3.4 Results

Line graphs show the actual and the averaged estimated coefficients of static friction on skin (Figure 18) and on wood (Figure 19). With the exception of Teflon on skin, friction was perceived, albeit underestimated. In some cases, roughness appears to have guided perception. For instance, the different grades of sand paper produce similar friction because roughness and contact area trade off against one another. The coarse paper is rougher but at the same time provides fewer contact points than the fine paper. The resultant friction is in fact comparable. However, the coarse paper was mistakenly thought to produce more friction than the fine paper.

With skin as reference surface, haptic exploration improved performance but estimates remained far from perfect. Teflon in particular was grossly mis-estimated. The overall results showed significant main effects of Material (F(5.7, 342.4)=22.85, p<.001, partial η^2 =.27) and Reference Surface (F(1.0, 60.0)=17.80, p<.001, partial η^2 =.23). In addition, the effects of Condition were more pronounced for the reference surface of skin; the interactions of Material x Condition (F(17.1, 342.4)=2.92, p<.001, partial η^2 =.13) and between Material x Surface (F(7.9, 475.2)=2.87, p=.004, partial η^2 =.046) were significant. The interaction of Material x Surface x Condition was also significant (F(23.8, 475.2)=1.69, p=.023, partial η^2 =.078). Contrasts revealed that performance was poorer in the photo condition compared to the haptic condition (p=.023) and the haptic-visual condition (p=.007). The latter two did not differ significantly from one another or from vision alone.

The post-experimental questionnaire revealed that most participants attempted to use all available information and that they tried to find out which material they were confronted with. After identifying the material, they estimated the friction on the basis of their experience. Perhaps some erroneous estimates could be ascribed to such cognitive influences upon friction estimation.

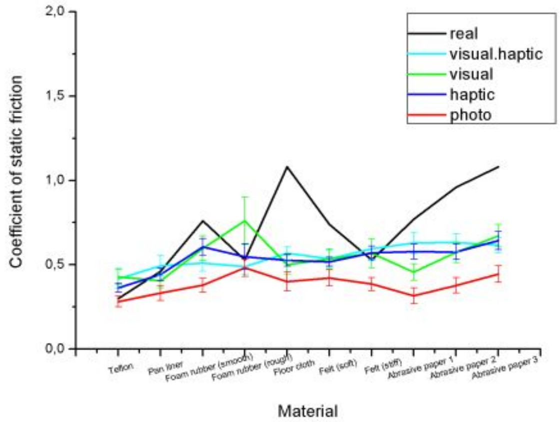

Figure 19: Actual and perceived coefficients of friction between **wood** and the respective materials. The solid black line corresponds to the actual angle of the slope at which the tile would start to slide. The other lines represent subjective judgments averaged across all participants of each group respectively. Error bars indicate standard errors of the mean.

In sum, static friction between a number of different materials and the reference surfaces skin and wood were picked up, but only to a limited degree. Vision alone does transport information about the relational property of friction. This ability to see friction is attenuated but still present when photographs are used. Thus, high-resolution detail appears to be crucial. Surprisingly, haptic cues were not superior to visual cues and even in combination only tended to improve performance. Friction is generally underestimated, with the exception of Teflon and wood, which was grossly underestimated. Multisensory information did not help compared to unisensory information. It appears that multiple information sources improve the perception of simple properties such as roughness (Lederman & Abbott 1981; Lederman et al. 1986), but fail to contribute in more complex cases of assessing friction. When visual information was reduced, not surprisingly, this affected friction judgments negatively. The photo condition produced notable judgment errors. It would be interesting to find out if this degradation could be compensated for by providing haptic cues together with the photographs. Note, however, that the photographs were able to produce estimates that correlated with actual friction. Thus, some information about roughness is preserved in the photo and can be accessed. The relational property of friction appears to be qualitatively different from and not reducible to roughness.

2.3.5 Friction experiment with manipulated visual appearance

The preceding experiment has shown that observers are able to gain some information about friction by visually inspecting the two involved surfaces together exhibiting this complex property. Given this ability, we should be able to isolate some of the relevant visual surface features upon which this ability is based. In a second friction experiment, we limited the reference surface to wood, and manipulated the visual properties of a select number of surfaces, namely Teflon, foam rubber, and sand paper. Among the changes in visual properties were factors that should influence perceived roughness and thereby potentially also friction, such as convolving the picture with a wave pattern, or changing the contrast in the picture.

2.3.6 Method detail

55 volunteer subjects (23 men and 32 women) participated in the study. They were recruited at the campus of the Johannes-Gutenberg University of Mainz and at a nearby supermarket. All participants were naive with respect to the purposes of the experiment. Their average age was 31.8 years ($SD = 12.6$ and a range from age 16 to 59).

We took some of the pictures of the tiles used previously. The pictures were taken on a Fuji Finepix S5500 digital camera (four megapixels) with a resolution of 1420 x 950 pixels. One reference picture each of coarse sandpaper, structured foam rubber, and Teflon were chosen. Then these reference pictures were modified using four special effects provided by Adobe Photoshop Six. Five visual effect conditions (Filter) were thus created for each of the three materials (see Figure 20 for the case of sand paper):

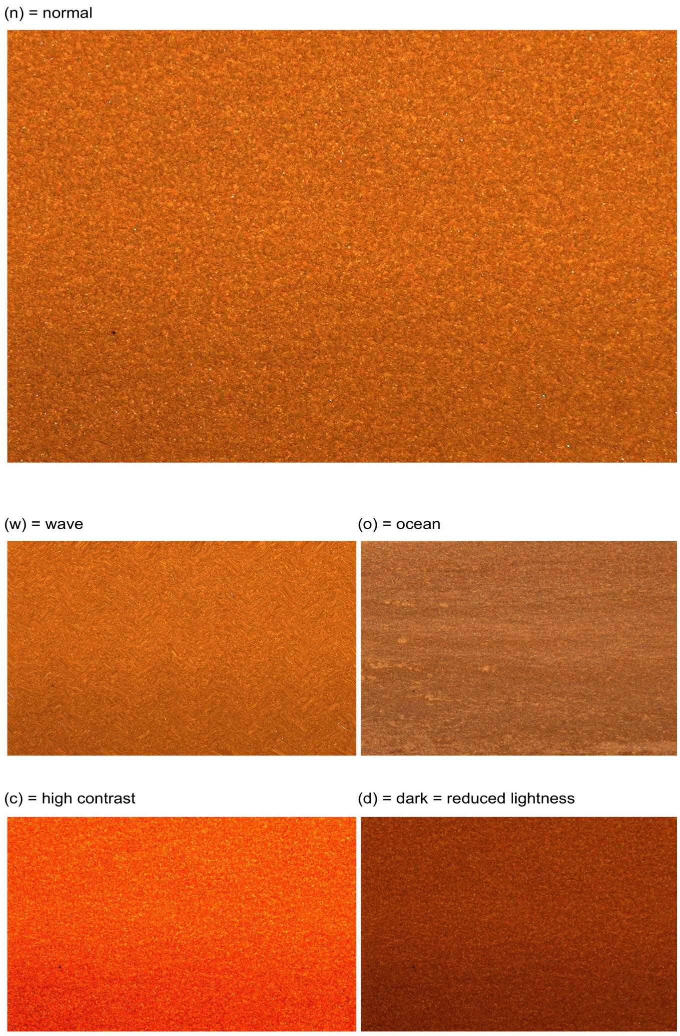

Figure 20: The reference picture (n) of the sand paper tile, and the four filter effects applied to the reference picture: ocean effect (o), wave effect (w), reduced lightness (d), and enhanced contrast (c). Note that all pictures were of equal size in the experiment.

1. Normal: The reference picture was the original photo of the surface without any special effect.
2. Ocean: The original photo was convolved with the structure of an ocean surface. A photograph showing the ocean from above with its waves was put as a new layer upon the original photograph with an opacity value of 25%. It added a look reminiscent of structured wood to the photograph. We hy-

pothesized that the added structure would increase perceived friction.

3. Wave: This filter introduced a wave pattern into the picture. This distortion effect was used with the parameters Number of Generators (5), Wavelength (Minimum 10 Maximum 120), Amplitude (Minimum 5, Maximum 35), Scale (horizontal 100%, vertical 100%), Repeat Edge Pixels (On), and Type (Sine). This filter distorts the original structure in the pattern of sine waves. We hypothesized that here, the added structure would not change perceived friction because waves are regular and smooth compared to the ocean texture.
4. Dark: The lightness of the surface was reduced uniformly by 50% (parameter setting: 50). We hypothesized that this would reduce detail, which would decrease perceived friction.
5. Contrast: The contrast was uniformly enhanced such that the according parameter was raised to +50. We hypothesized that the added contrast would emphasize roughness and thereby increase perceived friction.

The photos were printed on high-quality photo paper and shown to the volunteers in succession. The "normal" reference version of one material was always shown first, and then four different versions of the same material were presented in changing pseudo-random orders, for each material respectively. All possible sequences of the materials were presented to different observers. They were asked to imagine the surface shown on the photograph as being the surface of the ramp itself. The same ramp as before was used (see Figure 17), but subjects were not allowed to touch its actual wooden surface. Then they were asked to decide how steep the ramp would have to be set for a wooden tile to start sliding down on the shown surface. The tile of wood was shown to them beforehand and they were asked to touch it. Then they had to put the ramp at the angle at which they thought the wooden tile would just start to slide. As before, we measured the height of the ramp setting in centimetres. With this information, we calculated the angle with $\sin(\alpha)$ = height / ramp length = height / 44cm and finally the resulting estimated friction coefficient for all surfaces.

2.3.7 Results

Figure 21 shows the estimated friction coefficients for all three materials averaged across all filters and across the respective reference surface. Friction between wood and foam rubber was judged to be highest, friction with sandpaper was judged intermediate, and friction with Teflon was judged to be smallest. Figure 22 depicts the overall averages by Filter (visual effect). Figure 23 shows the interaction between Material and Filter.

A repeated measurement analysis of variance with Material and Filter as within-subject factors and gender as between-subjects factor was conducted on the judged friction coefficients; F-values were corrected by Huynh-Feldt as necessary. Material had a significant effect on estimated friction ($F(2, 106)=9.54$, $p<.001$, partial $\eta^2=.15$). Foam rubber and paper did not differ, but both were judged to produce more friction than Teflon ($p<.001$ and $p<.003$ respectively).

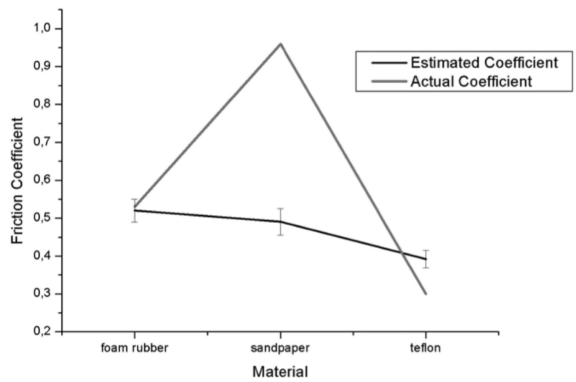

Figure 21: Estimated friction coefficients for the three materials independently averaged across all filters, and the actual coefficients for the three materials on wood. Error bars indicate standard errors of the mean.

The factor Filter also had a significant influence on the estimation of friction ($F(4, 212)=5.351$, $p=.001$, partial $\eta^2=.092$). The unfiltered stimuli were judged to produce the smallest amount of friction, and all filters appeared to increase the subjective coefficient of friction. Figure 22 shows the estimated friction for all five filters averaged across all three materials. The contrasts between the estimated friction coefficient values for "normal" and "ocean" (p<.024), "normal" and "dark" (p<.001) and "normal" and "contrast" (p<.023) were significant. Because of the sometimes variable judgments, the individual contrasts between "normal" and "wave" as well as "contrast" and "dark" failed to reach significance.

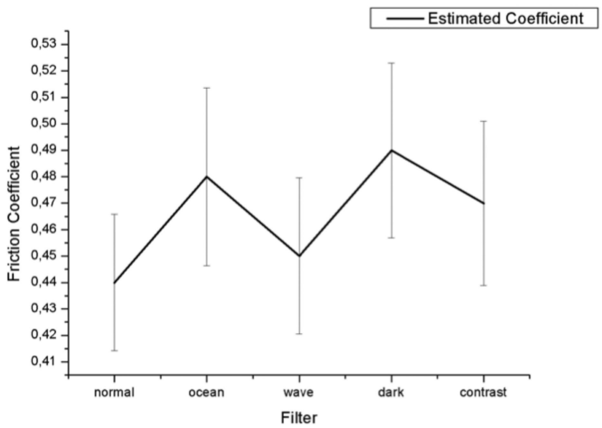

Figure 22: Estimated friction coefficients for the five filters averaged across the three materials. Error bars indicate standard errors of the mean.

We also found a significant interaction between the factors Material and Filter (F(8, 424)=3.99, p=.002, partial η^2 =.070). As visible in Figure 23, this interaction was mainly due to the immunity of Teflon to all filter manipulations and to the special effect of the increased contrast on foam rubber. Now let us have a closer look at the three materials and how they fared with the different filters. Participants could judge the friction between wood and the shown surfaces rather well, with the exception that the friction of sandpaper was underestimated. For some reason some of the grittiness and roughness of sandpaper has been lost in the photos, whereas no such loss occurred for foam rubber and Teflon. To the experimenter, the surface of sandpaper also did not look as rough as it did in real life.

Teflon on wood was clearly judged to be the most slippery surface. Interestingly, the estimated differences between the Teflon reference and its filter-treated variants were very small compared to the other materials (see Figure 23). Presumably, Teflon generally looks so slippery that a ceiling had been approached and the filters could not significantly change the low friction ratings of Teflon. The surfaces that were treated with "ocean" looked like rough wood; the manipulations "contrast" and "dark" seemed to make the structure clearer. The filter "wave" had a smaller influence on the estimations. Participants often said that they found it difficult to classify the wave-treated surface.

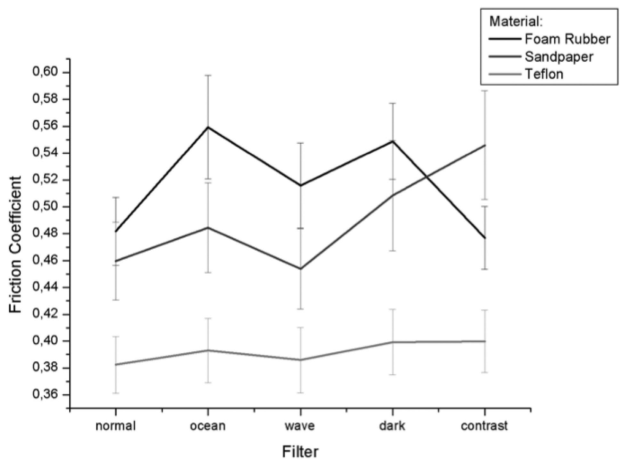

Figure 23: Interaction between the two factors Material and Filter. Error bars indicate standard errors of the mean.

The results of this experiment clearly show that irregular additional structure—as introduced into the surface by convolving the picture with the ocean pattern—causes the perception that the surface is less slippery. This was the case for all surfaces that were not extremely slippery to begin with. Other than hypothesized, reducing the lightness of the surface also tended to produce higher ratings of friction. Increased contrast, on the other hand, produced mixed results. Sandpaper with increased contrast was judged to cause more friction. Contrast had a smaller but similar effect on Teflon. However, when applied to foam rubber, increased contrast had no effect. Taken together, these effects demonstrate that visual aspects of a surface, such as its microstructure, its lightness, and its contrast co-determine how slippery it is judged to be with respect to a given reference surface. Note, however, that the reference surface was always wood, and simple roughness judgments may have guided the friction estimates.

To summarize the friction case study, we conducted two experiments to assess whether observers are able to visually perceive the complex relational property of friction between two surfaces even when not allowed to touch the surfaces. They were able to do so with limitations. Observers generally tended to underestimate the degree of friction. An underestimation of friction as observed in these two studies could be regarded as a conservative approach to judging the grip force required to successfully grasp objects. Using more force than necessary rarely leads to disaster (consider raw eggs), whereas too little grip force causes an object to slip out of our hand and fall.

The first friction experiment compared judgments based upon visual inspection alone, and then after visual and haptic inspection. Vision in and of itself provides valuable information; additional haptic information added surprisingly little. The second experiment explored the particular visual properties that make surfaces look more or less slippery, but note that the reference surface always remained unchanged. Subjects likely differentiated between surfaces of different roughness insofar as roughness (simple property) and friction (relational property) were correlated. Errors were large in particular when the relational property to be judged was variable. Perceiving Teflon as very slippery (with respect to skin) when it is indeed quite the opposite is a grave perceptual error, but it is not very meaningful to call the error an illusion$_d$. A perceptual miscategorization of the relational property of friction between surfaces might be a more appropriate description.

3 Conclusion

I have attempted to argue that we need to reconceive the notion of what an illusion is. In the context of the traditional line drawings used over a hundred years ago to illustrate the shortcomings of vision, illusions$_m$ have begun to misguide our thinking about normal perception. Illusions$_m$ do not indicate the error-prone nature of visual perception. On the contrary, they tend to be small compared to the many illusions$_d$ that go unnoticed on a regular basis. To illustrate that this is the case, I have used two examples from the domain of complex relational properties. This choice was based on the conviction that perception of everyday objects always necessarily includes judgment (be it in terms of Helmholtzian unconscious inference, or be it in terms of private models that may or may not become transparent to the perceiver). The notion that illusions$_m$ should be of interest because they reveal the workings of how the visual system derives percepts from simple sensations is not useful. It is not useful because an illusion$_m$ only becomes manifest by a comparison process that is at least as fraught with cognition as is the perception of everyday relational properties. We have used the classical stick in the water and the equally classical Ebbinghaus illusion to illustrate that illusions$_m$ only become manifest if a cognitive operation is performed (i.e., a perception-inference-cycle when moving the stick or comparing the circle to a reference circle known to be of identical size).

It is also impossible to investigate illusions as merely phenomenal problems. And it is ill-conceived to limit the study of visual perception to seemingly simple phenomena that end up requiring cognition after all. Perceiving is to make perceptual judgments, be they explicit (e.g., by saying which of two objects is larger), or be they altogether implicit, or merely amenable to consciousness by an act of attention (e.g., by determining hand-aperture when grasping an object). It is thus impossible to investigate illusions as purely perceptual errors. Instead, illusions always have a cognitive component in the sense that they require an act of comparison or inference. This holds for all illusions$_m$, even if they may not be amenable to consciousness. To take illusions as a discrepancy between what we see and what there is, is doubly mistaken. First, there is always a discrepancy (illusion$_d$) between a visual percept and the object in the world to which it refers, namely the stimulus. And second, only in rare and simple cases do we notice this discrepancy (illusion$_m$). The discrepancy is owed to the underspecification problem (UP), the qualitative information gap between the two-dimensional retinal image and the richer three-dimensional percept. The UP puts the perceptual system in a position from which it has to draw additional information from memory, from inference, or from internalized structures that have been acquired throughout evolution. Such structures have been suggested to include that objects are three-dimensional, that light comes from above, that gravity acts along the main body axis when standing or walking, or that the brightest patch in the visual field is usually "white". Internalized structures gain particular weight if the stimulus is poor. This is the case when looking at simple line drawings and it is all the more the case when looking at relational properties. The quality of solutions to the UP differ greatly as the function of the task demands, but not necessarily as a function of the complexity of the stimulus. On the one hand, the perceptual system achieves performance that seemingly approaches perfection where precise motor action is required in personal space. On the other hand, in more remote action or vista space (for a very useful taxonomy of space see e.g., Grüsser 1983) some blatant errors are made. Our perception often defies the most basic laws of physics. More often than not do these errors go unnoticed. To illustrate how crudely our perceptions approximate reality even in personal space, we have explored errors in balancing objects and judging the slipperiness of surfaces. When it comes to these relational properties, our perception falls far from the truth. It appears that the errors tend to be as large as they can be without interfering with the perception–action cycle required for adequate or acceptable action. The evolutionary fine-tuning would minimize error until it is no longer relevant for survival. In this sense, normal perception (i.e., the illusion$_d$) is a satisficing solution. The magnitude of the perceptual errors many observers make is in the league of errors associated with probability judgments (see e.g., Kahneman et al. 1982) and syllogistic reasoning, as opposed to the much smaller errors typically associated with perceptual illusions$_m$.

Our perception, just like our cognition, has developed to find solutions to problems that suffice. When reaching for an object, perception is accurate enough not to knock it over but to grasp it (most of the time). When judging a surface, it is accurate enough that we do not slip (most of the time). These examples are noteworthy because they do not relegate perceptual error to remote vista space, where precision would not matter. Toppling over an object or falling on a slippery slope concern us in personal space.

In essence, the UP is solved with remarkable accuracy for simple properties of objects within our domain of interaction. However, as soon as the perceptual properties become more complex and involve the relation between two or more objects, the perceptual system can no longer solve the UP with any degree sophistication that goes beyond the level of medieval physics. But rather than giving up and seeing astounding illusions everywhere, the system degrades gracefully and builds theories that suffice for the purpose at hand. Their deviation from reality is not experienced. These perceptual theories may be thought of as more or less universal tools for upholding a meaningful world (in the sense of Shepard 1994); however, it might make more sense to think of them as universal tools with a private touch that accommodates individual perception-action requirements. A hockey player or a juggler will for instance have developed private models, be they unconscious or amenable to introspection, about friction or balancing that are more sophisticated than the layperson's. Note that these models need not be explicit, in the sense of a perceptual process, of which the cognitive elements cannot be separated out.

Such private adjustments and elaborations when solving the UP need not be made in the case of classical geometric-optical illusions$_m$. I hope the above examples and case studies have shown that ilusions$_d$, such as the Luther illusion, do not require detection, and illusions$_m$ that become manifest, such as the Ebbinghaus illusion, can be upheld because their limited magnitude makes them irrelevant for action.

This raises the questions why illusions$_m$ arise at all. Illusions$_m$ might arise as mere epi-phenomena or as meaningful warning signs for the system to signal that a perceptual fine-tuning is needed. The epi-phenomenon interpretation would suggest that the juxtaposition of two contradictory percepts is a fluke and happens per-chance every once in a while. Optical illusions$_m$ are merely collections of such flukes. The warning-sign interpretation would see in them the purpose of fine-tuning the perceptual system. If the perceptual system subserves action, it would ideally minimize error (illusions$_d$), and one mechanism to do so would be the experience of illusions$_m$. It is unclear, however, why illusions would have to become conscious for this fine-tuning to work. Would the necessary re-direction of attention require the experience of an illusion$_m$? Be this as it may, the system does not even notice error—let alone attempt such fine-tuning—when it comes to perceiving relational properties. Even an approximate veridical perception of relational properties is out of reach of the perceptual system. The system merely arrives at the first solution that satisfies our action needs. A flashy epi-phenomenon or a warning system, as indicated by manifest illusions$_m$, is not useful here, as the discrepancy between percept and reality is too large.

Now, one might ask about cases where the error is exceedingly large and a warning may indeed be in place. These cases are rare; but they do, however, result in manifest illusion$_m$, and hence are compatible with the purpose of illusion$_m$ that we suggest. Take for instance the perception of pain in a phantom limb. Here the sufferer does notice the illusion$_m$. How can pain be so vividly felt in a limb that is no longer there? The warning function of this manifest illusion$_m$ is obvious. For instance, learned reflexes involving the absent limb need to be extinguished and reprogrammed. A more interesting case is the infamous rubber-hand illusion (Botvinick & Cohen 1998) or the full-body illusion that can be created in most observers by synchronizing their actions and perceptions with those of an avatar seen in a VR (Virtual Reality) presentation (see e.g., Blanke & Metzinger 2009; Blanke 2012; Botvinick & Cohen 1998; Lenggenhager et al. 2007). Only in such extreme cases does the error manifest itself in a complex relational case. We feel that we are someone or somewhere else and at the same time feel that we are not. It seems to take such extreme cases before we find a sizable illusion$_{d+m}$ that deserves the name “illusion”.

In most cases, we can adjust perceptions once we notice that they are erroneous, be they ball trajectories or balancing properties. However, this adjustment process is painfully slow and may have to draw on early stages of perceptual and cognitive development. It does not take center stage, and some theoreticians would claim that the adjustment process converges on a veridical understanding of the world (Gibson 1979 calls this “attunement”). Others claim that many perceptions are useful precisely because they do not match or converge on the world (e.g., the multimodal user interface theory of perception, Hoffman 2010). The satisficing nature of private perception may not require a perfect solution of the UP in many cases, as long as the slips and falls remain limited to a tolerable number.

Acknowledgements

Markus Homberg, Cornelius Mülenz, and Mana Saadati helped collect and analyze the balance data; Daniel Oberfeld provided valuable input for the experimental designs; Elsa Krauß, Markus Landgraf, and Laura Längsfeld carried out the friction experiments.

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