CHAPTER 1

A Sense of Space

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We tend to perceive and understand the world in a spatial manner: distances, orientations, places, and sizes. These spatial features are integrated in a three-dimensional framework, and are extended to build internal notions of composite objects, layouts, and trajectories. In order to further appreciate the spatial activities of the human brain, let us start with a common example from daily life. Say your best friend has moved to a new place, a cute cottage on the edge of town. She invites you to come over next Sunday for a drink and gives you a detailed, though not necessarily comprehensive or accurate, route description. This first part of the example poses already a main decision to be made: do you keep the verbal instructions or do you somehow turn them in a more map-like representation? Choosing the first option will force you to translate the verbal commands in appropriate spatial behaviors along the way. Choosing the second raises another question: what exactly is the nature of a spatial representation. Which are its intrinsic qualities and how does it map to the outside world, that is, physical space?

Whatever your representational decision, you take the next step in reaching your friend's new place. Since the route is quite long, you choose to take the car. Finding your car keys becomes the next challenge, requiring spatial search (see chapter 4: Multisensory Perception and the Coding of Space). The difficulty here lies in scanning the visual world with a multitude of objects and locations trying to minimize the length and number of eye movements. Search efficiency clearly would benefit if you have some sort of spatial memory, either of where you placed them an hour ago or where you typically keep them (see chapter 7: Keeping Track of Where Things are in Space—The Neuropsychology of Object Location Memory). Keeping track of where we left things is a typical burden of daily life (Fig. 1.1).

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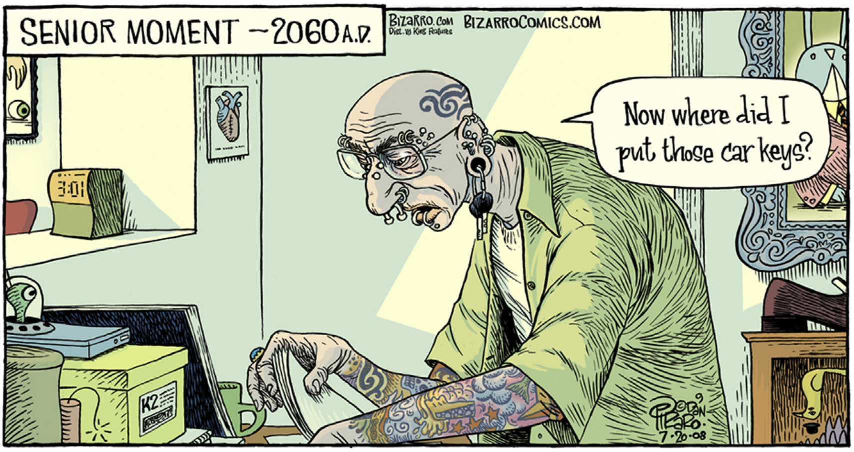

Figure 1.1 Senior moment, from http://bizarro.com/, illustrating daily life difficulties in remembering where things are.

Assuming you have managed to find your keys you can get on your way. Negotiating traffic in a dynamic world requires a multitude of spatial abilities. We need to accurately perceive distances and orientations (see chapter 2: On inter and intra hemispheric differences in visuospatial perception), both in order to avoid collisions and to take the appropriate turns. The spatial world is dominated by the visual sense but our other sensory systems also offer marked sources of spatial information. When focusing eyes and attention straight ahead, a car horn from the left will force you to quickly reorient and integrate sound with the vision of a rapidly approaching vehicle. Multisensory integration is a special capacity of the brain's spatial system (see chapter 4: Multisensory perception and the coding of space). While seemingly effortless and inevitable, connecting one modality to another is quite a complex feat. In the given case auditory space is coded quite differently than visual space even in the early perceptual stages (ie, a tonotopic coding vs a retinotopic coding). Hence, the question may arise as to how we have learned to merge the spatial inputs from our senses (see Box 1.2; see also chapter 9: How Children Learn to Discover Their Environment: An Embodied Dynamic Systems Perspective on the Development of Spatial Cognition).

Finally, you have managed to arrive at your friend's new place. You spent the rest of the afternoon discussing work, holidays, other friends, news of the world, and maybe your efforts in reaching the place. After a pleasant afternoon you drive back home again. Did you retain anything from your earlier exposure to the route? In other words how does our navigation system learn and maintain route information (see chapter 8: Navigation Ability)? Notice, that on your way home the route has to be travelled in reverse order. Recognizing when to take a turn now might depend on your ability to change spatial perspective. A particular problem occurs when suddenly part of the way is blocked and you have to plan a detour. Much later than intended, and completely exhausted you arrive home. Without thinking you drop your keys in a rather unusual place—the fridge when grasping a can of beer. Hence the next day a strenuous spatial search will start again.

Our sense of space is critical for successful interaction with the outside world, whether we use it to estimate the distance towards an approaching car, program the grasping movement to pick up a can of beer, plan a route towards a new destination, or remember a route travelled many times. Spatial cognition is concerned with the acquisition, organization, utilization, and revision of knowledge about spatial environments. Spatial cognition involves the set of mental processes underlying spatial behaviors and thinking. In order to be labeled as "spatial," information or the behavior it supports needs to involve processing of features such as place/location, size/shape, direction/order, extent/continuity, relations/configurations, connectivity/sequence, and hierarchy/dimensionality (Montello & Raubal, 2012). Admittedly there is the danger of circularity here by defining spatial cognition using terms like "space" or "spatial." It is not our aim to give an encompassing, unequivocal definition, but rather to offer a more global notion of what the concept spatial cognition is about.

1.1 ON THE DEFINITION AND MEASUREMENT OF (PHYSICAL) SPACE

Of course a real understanding of spatial cognition and the human sense of space should begin with specifying what exactly space is and how we can measure it. A formal definition of "space" would be something like *structured simultaneous presence*. This is a very general definition that applies to formal (or mathematical), physical and mental spaces alike. When mentioning "physical space" one usually has the intuition that it is something that is infinitely and continuously extended. This feeling is perhaps best characterized by Newton's definition II in the *Scholium* (Newton, 1687). Notice that Newton obviously struggled to come up with a clear definition. So will you, just try! Space has seemingly mysterious properties both in the large and in the small. The Euclidean plane of high school geometry has no boundary and its area is "infinite." The surface of the earth is also unbounded—you can't fall off—but its area is only 510,072,000 km^2. An arbitrarily small patch of the Euclidean plane contains infinitely many points. One calls the plane "continuous" in contradistinction to the chessboard, a "discrete" space containing only 64 points ("fields"), a "point" being—in Euclid's definition—"that which has no parts." In the centuries following the various notions of boundedness, the infinite, and the nature of the continuum have been extensively studied by mathematicians (Bell, 2005; Rucker, 1995). These topics were already discussed by the Presocratics (Lloyd, 1970), but it is probably correct to say that they continue to be as mysterious as they ever were. When Bernhard Riemann delivered his famous habilitation lecture (Riemann, 1854), he mentioned that we know only two spaces by immediate intuition, namely "the space we move in," and the "space of colors." "The space we move in" is what people usually mean when they mention "physical space." It should not be confused with the concept of "space" used in modern physics, which is a formal, mathematical structure. "Physical space" is a naive, folk-science notion. Perhaps one should say "real life" instead of "physical," for that is usually implied, but we will use the conventional "physical" here. "Physical space" is a concept that covers a wide area of phenomenology.

Closely linked to the question of how we define space, there is the question of how to measure it. Throughout human history almost every culture has developed or adopted some system(s) of spatial measurement, both for economic, political, and cultural reasons. The most important are measurements of length, size, area, and volume. One often uses length and size interchangeably, but typically size relates to specific objects, whereas length can also be used to indicate a gap between different objects. Thus a sieve[1] is an instrument that applies to size, but not to length. In many cultures another important spatial property is the angle, although it is not necessarily quantified. This is because right angles tend

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[1] A sieve (or "sifter") is a device that has numerous holes of some fixed size. It will pass objects that fit through the holes whereas it will stop larger ones from passing through. Thus it serves to separate smallish elements from large ones, say mustard seeds from peas. A template is a device that lets you check shape. A simple example it a taut wire—which is "straight"—commonly used by gardeners to ensure well-formed garden paths or lawns. Dividers (or "compasses") are used to compare or transfer distances from one place to another, for instance in drafting, or comparing distances on a map.

to be important, whereas others are merely considered "off." This does not apply to length, area, and volume, which range between very small (or even "nothing") to very large (or even "everything"), they denote "infinite" ranges, whereas angles live in a finite—although boundless—range.

The basis of measurement is *comparison*. There are many occasions where a mere comparison suffices, and a measurement proper is not even required. Common examples are the use of sieves, templates, straightedges or taut wires, dividers, and so forth. The most basic comparison is that of *spatial coincidence*, that is, two objects are identical with respect to the spatial property central in the comparison.

Every measurement consists of a comparison with a conventional gauge, or reference object. A gauge object can take on many forms, but it is always used in essentially the same way. An observer notices a "fit," that is to say, the act of comparison yields a judgment of "equality," or "no difference." This is the basis of virtually every form of measurement, not just spatial ones. In physics one recognizes only two types of measurement, namely, the counting of discrete objects, and "pointer readings," for example, determining a distance value by reading out the corresponding mark on a ruler. Because pointer reading involves the judgment of "no difference," for example, the coincidence of a landmark with the mark on a scale, it involves no phenomenal qualities. Consequently, Sir Arthur Eddington famously argued (Eddington, 1927) that all physical quantities are completely meaningless. Physical quantities are not *qualia*. The physicist reasons formally from pointer reading to pointer reading, allowing for very precise quantitative predictions.

Consider a simple example of measurement in line with the foregoing. Because beer is perhaps the most efficient way to conserve grain, beer has been an important commodity in various cultures. Beer has value in all kinds of bartering, so one needs to be able to quantify it. The Egyptians used beer and bread as the currency to pay slaves, tradesmen, priests, and public officials. Their economy was based on grain. Different from bread, beer cannot be counted, so one needs a method of measurement. An obvious way to do this is to select a suitable jar and call it "unit beer measure." This jug is kept in an official place (eg, a temple), and is constantly guarded by absolutely trustworthy heavyweights. When the jug is used, an official is present to ensure that it is filled in the standard way. When the standard jug is emptied into another, larger, one, one may scratch a mark to indicate the "full measure." Thus all beer merchants can obtain a "secondary standard," which necessitates a special police to make sure that they keep it honest. No "theory of volume" is necessary to implement this technology. All that is needed is the judgment that the standard jug is full. Any fool is able to check that.

Notice that there are other ways to measure amounts of beer. For instance, it is not that hard to implement a method based on *weight*, choosing and guarding a standard stone. If you have both a standard volume and a standard weight, you might discover that the same full measure always has the same weight. It is these remarkable empirical facts between physical quantities that render such measurements *useful*. One should not fail to appreciate the fundamental importance of this point, however straightforward it might seem.

Consider the measurement of another spatial property: length. Here most cultures have used a conventional rod, or a rope with two knots. A rope can be used to measure length "around the corner," whereas the rod only applies to stretches that are fully exposed. You can try to find a rod that has exactly the same length as two copies of the standard rod placed in tandem. Or you can break a copy of the standard in two equal parts. Thus you can have rods of "two rods long" and rods of "half a rod long." In advanced cultures this leads to rods with a series of marks, so called "rulers," that make it easily possible to estimate arbitrary lengths. Notice that all that is ever needed to implement all this are judgments of spatial coincidences. No phenomenal qualities are involved. These are examples of Eddington's "pointer readings."

Why did length measurement with a rod become so useful? Well, mainly because *a rod is a rod*. This sounds trivial, but it is not. The point is that a rod does not change when you displace it over arbitrary distances, or when you put it in various spatial attitudes. Thus the rod allows you to compare the height of a building with its frontal width, or the size of a Celtic sword to a Roman one, even when these artifacts are a thousand miles apart. This is very remarkable if you come to think of it. And convenient too! (Fig. 1.2).

Length and volume fairly easily yield to the method of comparison. This is very different with *area*. Because areas come in many different shapes, it is not at all obvious what gauge object to use. There may be infinite possibilities! Historically one has employed various measures such as the "*Morgen*" (used in Germany, Poland, the Netherlands, and the Dutch colonies, including South Africa and Taiwan). A "morning"—the literal translation—is the amount of land tillable by one man behind an

Figure 1.2 Graeco-Egyptian God Serapis with measuring rod. Notice the equal subdivisions. This rod allows one to define "length" (of anything) in terms of pointer readings.

ox in the morning hours of the day. Other measures include the number of olive trees a piece of land will accommodate. Early geometrical methods were often based on the *perimeter.* For instance, when Queen Dido was stranded on the coast of North Africa, she asked the Berber King Iardas for a bit of land as a temporary refuge, only as much as could be encompassed by an oxhide. She arrived at an agreement, and proceeded to cut the hide in thin strips, enough to encircle a nearby hill. This famously solved the isoperimetric problem—the circle has the shortest perimeter for a given area, and established the city of Carthage c. 814 BCE. A perimeter measure can be made to work for areas, but only if you use it only for a specific set of shapes, say squares or circles. A common instance is the forester measuring tree trunks with a tape measure. But perimeter-based area measures remain inconvenient. For instance, a square of twice the circumference of a unit square has four times the area of that unit square.

In agricultural societies area measurement was so important that the science of geometry (literally "land measurement") became established.

Figure 1.3 Anglo-Saxon plowmen using a rod.

This enabled areas of land to be measured by angle and length, albeit at the cost of nontrivial calculations. This can be considered the first step towards a formal description of space. A *geometry* is a set of rules with which we describe size, shape, position of figures, and the properties of space. Thus, although our current formal theories are remote from "land measurement," *geometry* remains an apt term (Fig. 1.3).

Although the official units for length, and so forth, are extremely important, it should not be forgotten that there are also convenient standards that are always literally "at hand." We mean such units as "a thumb," "a palm," or "an arm," "a step," "an hour's walk." These depend upon the fact that all humans are roughly of the same size. Even better, a mature human remains at fairly standard size for dozens of years. As Helmholtz remarked, "we use our legs as dividers." A "pint" was the volume—of beer—that was nourishing, but not too much. Aren't we all in sympathy with that?[2] Such "natural units" have been used for centuries in the Western world, and are still in frequent use in many cultures. Of course, the basic principle remains unchanged, it is only the "gauge objects" that are differently defined. The fundamental judgment is invariably that of equality, typically the spatial coincidence of two objects. No *qualia* are involved.

So where then did the meanings go? Well *they took refuge in the gauge objects*. The method of comparison manages to dodge matters of meaning

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[2] Nowadays an "imperial pint" is 568.26 cm^3. Does that "make sense" to you? Of course, it isn't designed to do so. "568.26" is simply a meaningless number. "1" pint of beer is what many persons "understand." Here the meaningless number "1" stands for the gauge object "pint," which is "nourishing, but not too much."

Figure 1.4 Poster by the British Metrication Board of the 1960s, converting 36–24–36 (the units—inches of course—not even indicated in the poster) to metric units (millimeters). "Lady Metric," a British C.I.T.B. (Construction Industry Training Board) poster of the late 1960s. "Miss Metric" Delia Freeman thought 914–610–914 made her look fat. Certainly, most people of that time intuitively understood "36–24–36." But numbers are just numbers, inches or millimeters are the corresponding qualities. Although conceptually equivalent, people apparently also "carry units in their heads."

and quality. The "mystery" is stored away with the gauge objects. Thus "a length of ten rods" is a formal statement that does not require one to understand "the nature of length" at all (Fig. 1.4). This is even more striking for cases like temperature, radiance, magnetic flux, and so forth.

So now we know how to measure spatial properties, do we understand any better what "physical space" is? Not really. Eddington (Eddington, 1927) was right in stating that physics is nothing but recording pointer readings, and formally reasoning from these to the prediction of possible pointer readings. This has nothing to do with an understanding of the objects being measured, in this case "physical space" or perhaps better the space you move in. If there is understanding somewhere, it is in the reasoning applied to the pointer readings. This can be regarding as a model of the area of interest. The theories of the physicist are of such nature. An understanding of this came rather late. Possibly Heinrich Herz (Herz, 1895) was the first one to offer a coherent exposition. The theories, or models, are usually not unique, and they are only provisionally, and almost certain only temporally, "true." They are best understood as our "user interface" (Hoffman, 2009). The interface allows one to interact efficiently with the world, but it should not be understood as being about some final or fundamental way "the world is" (Gibson, 1979). This insight certainly holds for "space" too. Thus "physical space" is perhaps best defined as your (that is to say, the academic society's) preferred interface. For many of our purposes that will be mainly Euclidean geometry, although for some purposes, like painting a landscape, projective geometry might be preferable, (ie, railway tracks, which are parallel lines in Euclidean space, meet at the horizon at a "vanishing point"; see also Box 1.1), and for aircraft transport Riemann geometry is advised (ie, airlines schedule New York—Singapore over the North pole using Riemannian geometry).

BOX 1.1 From 2D to 3D Space

One might argue that vision is the prime spatial sense. Intriguingly the initial visual input (ie, light falling on the retina) is two dimensional, whereas what we perceive is three dimensional (ie, depth). "From 2D to 3D space" suggests a well-defined progression in the processing of optical structure. Basically, and greatly simplified, first a "2D representation" is constructed on the basis of local "features" that have been extracted by such mechanisms as "edge finders," "corner detectors," and so forth. Then a "3D representation" is constructed on the basis of a variety of "cues" derived from the 2D representation. Such ideas have been acknowledged for ages, but might be said to have been canonized by David Marr in the 1970s (Marr, 1982). Alternatives (best known from the 1950s and 1960s) have particularly been advocated in the work of James Gibson (Gibson, 1950) that the observer directly picks up 3D information from the—partly self-generated through body movements—spatiotemporal optical structure. In that case there simply *is no* 2D stage. These notions are miles apart.

Conceptual complications are due to the fact that humans are able to obtain both 2D and 3D impressions from *pictures*, something animals are apparently unable to do (Deruelle, Barbet, Depy, & Fagot, 2000). Pictures are of particular interest here because they are doubtless 2D as physical structures. Pictures thus often stand for "retinal image" or "optical input" in scientific debates. The remarkable fact of 3D pictorial vision has not failed to puzzle many researchers, who consider the very notion of "monocular stereopsis" as paradoxical. The easiest way out of the dilemma is to simply ignore the phenomenon. Thus Gibson would understand a "picture" only as the illusion of a window opening up on an actual scene. Yet "pictorial space" is a striking

(*Continued*)

BOX 1.1 From 2D to 3D Space—cont'd

aspect of visual awareness (Ames Jr, 1925; Claparède, 1904; Schlosberg, 1941), to ignore this is hardly honest science. It is also important culturally. Artists rarely try to paint an illusory window; instead they rather tend to stress the existence of the physical picture plane. Pictures are aesthetically attractive *because* they are simultaneously 2D and 3D. From a Gibsonean perspective that is fully unpalatable.

In perceiving (interpreting) pictures as 3D scenes multiple cues are used. Cognitive processes are based on the interpretation of these "cues." Some cues are fully arbitrary, in the sense of being culturally determined. For instance, suppose you look a Caucasian person in the face and suddenly notice that the spectrum of scattered radiation skews towards the low energetic photons. This "reddening" will typically make you aware of "shame" in the face. Importantly though, there is no direct, necessary connection between the emotion of shame and turning red. This is a famous example by Bishop Berkeley (Berkeley, 1709) who may be said to have introduced the technical notion of "cue." Clearly "blushing" is not due to Gibson's "ecological physics," but is culturally determined.

In contradistinction, the blue tinge, which is often seen in landscapes and is a potent spatial cue for remoteness, can be interpreted in terms of the optics of the atmosphere. Clearly the latter and other cues depend on simple, direct physical causation. Another well-known example as such is the shading cue. A linear gradient of retinal illuminance is often experienced as the curvature of a surface in the scene in front of you. See for example Fig. 1.5. It is important to notice here that the 3D interpretation of 2D cues almost obligatorily invades our awareness. We would have great difficulties in deciding not to see any depth in Fig. 1.5.

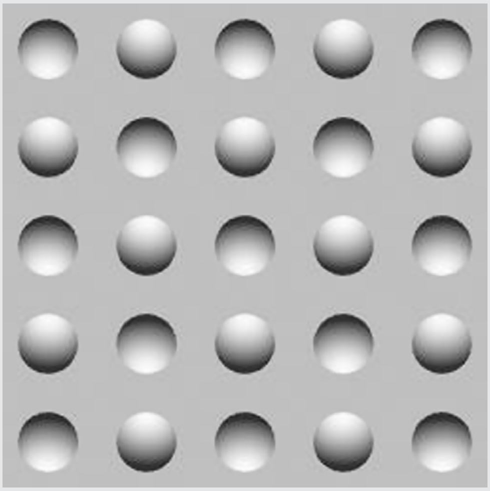

Figure 1.5 "Shape from shading." Most people see 3D "pictorial depth" here and cannot choose to not see it.

Given that there are multiple geometries to measure and describe (physical) space, we may wonder how our brain is tuned to appreciate space. Or in other words, what is the geometry of mental space. It is often said that Kant, one of the major philosophers of all time, displayed tunnel vision when he discussed space, perhaps because he never left Königsberg (present day Kaliningrad). However, another way to look at this is that Kant was not talking about "physical space"—whatever that may be, for Kant a mere "*Ding an sich*"—at all, but rather about *cognitive space*. Then he might well have been right, for most people intuit the Euclidean plane as "natural," whereas they experience a strong aversion against the notion of there being none, or infinitely many parallels to any given line.

1.2 SPATIAL REFERENCE FRAMES

In the foregoing, we saw there exist many mutually distinct formal geometries and there are various ways in which to operationalize spatial relations. But no matter what geometry we apply to understand the space surrounding us, we always have to decide on some appropriate frame of reference. Places and directions can only be determined relative to a chosen frame of reference (Mou & McNamara, 2002). A reference frame is a unit or an organization of units serving as a coordinate system with which spatial properties of objects in the world can be determined (Levinson, 2003). Reference frames typically include the notion of a "ground" object or unit with respect to which places are individuated. Klatzky and Wu (2008) point out that a reference frame gives a set of parameters that localize and orient an entity in space. A typical example of such parameters is the x,y,z that is used to define a point in Euclidean space. In a similar vein Wang (2012) distinguishes reference origin and reference direction or axes as basic elements making a reference frame system. Howard (1982) notes that a reference frame is an attribute of an object that does not normally vary and against which variations in the same attribute in other objects perceived at more or less the same time can be judged.

It has long been acknowledged that multiple spatial reference frames may exist and determine our perception, conception, and action in/of space at a given moment. We may employ these reference frames,

Table 1.1 Reference frames and their alleged functional properties

Subtype	Tasks/functions	Chapter
Egocentric frame of reference		
Retinotopic	Eye movements, attentional movements	5
Head	Attention movements	5
Shoulder	Reaching, grasping	3
Hand	Haptic object inspection and object handling	3, 4
Whole body	Linguistic communication (relative reference frame; Levinson, 2003) and sequential route learning and path integration	6
Allocentric frame of reference		
Single object	Object-based attention and linguistic communication (intrinsic reference frame; Levinson, 2003)	5, 6
Multiple objects	Object localization	7
Landmarks	Allocentric navigation; survey mapping	8
Environmental geometry	Object localization and allocentric navigation; survey mapping	8
Earth-bound features	Spatial thought and linguistic communication (absolute frame of reference; Levinson, 2003) and navigation in natural environments	6, 8

depending on the current perceptual conditions, task at hand, and personal preferences and skills (Table 1.1).

Reference frames have been described by a number of different terms and distinctions in the literature. A first main category includes so-called egocentric spatial reference frames: positions and objects in the outside world are coded relative to parts of the observer's body. Subclasses are retinotopic, head-centered, and body-centered. The latter in turn may include trunk/body midline, shoulder, and hand. Egocentric reference frames particularly play a role in direct motor actions such as grasping or pointing towards an object. In these situations it is vital to code the target object with respect to its spatial relation (distance, orientation) with a part of the body. In our example, picking up the car keys requires one to relate the keys both to the shoulder and the hand frame (see chapter 3: On feeling and reaching: Touch, Action, Body Space). Notably other cognitive activities may also engage egocentric (like) reference frames, such as navigation (see chapter 8: Navigation Ability) or communication (see chapter 6: Tell me Where to Go: On the Language of Space) (cf. Wang, 2012).

A second main category of reference frames is formed by the allocentric reference frames (sometimes also called exocentric reference frames). Here constellations of units outside the observer are used to offer an environment-based point of reference. Searching the car keys in our example could be facilitated by remembering where we left them in the room. Allocentric reference frames offer perspective independence, that is, the coding of positions is independent from your own current position or orientation. Different cues are used in allocentric reference frames: single objects, the relations between multiple external objects, landmarks (eg, salient, distal objects), and the geometry of an extended surface or boundary (cf. Chan, Baumann, Bellgrove, & Mattingley, 2012), for example, the shape of the room you search for your keys, or the contours of the landscape you drive through when visiting your friend. A special class of (allocentric) cues involves overarching features of the earth as a whole, such as perceived direction of gravity or the sun's azimuth, specifying cardinal directions (eg, North, South). Levinson (2003) uses the term absolute frame of reference whenever these more absolute place codings occur. Arguably repeated cross-checking with multiple environmental cues is needed to instantiate this frame of reference.

The reference frame chosen in turn determines the spatial representation employed in a given situation (see also below). Different reference frames may engage distinct neural networks in the brain. A popular division is that between the dorsal cortical route supporting egocentric spatial referencing and the ventral route involved in allocentric referencing (Milner & Goodale, 1995; Neggers, Van der Lubbe, Ramsey, & Postma, 2006; see also chapter 5: Spatial Attention and Eye Movements). An important consequence is that this makes it possible to observe qualitatively distinct disorders bound to selective impairments in a particular reference frame. The classical example is object-based spatial neglect (Driver, 1999) versus neglect for one side of egocentric space (see Committeri et al., 2004). We will address in more detail the underlying neural machinery of reference frames and representations when discussing particular spatial cognitive domains in the other chapters in this book.

1.3 THE NATURE OF SPATIAL REPRESENTATIONS

The reference frame chosen forms a main characteristic of the spatial representation employed in a given situation. But what exactly is the nature of this representation and the format of the information it contains? The example of the visit to your best friend's new home started with the question of whether to keep the route instructions in their original format or instead whether to use them to build a more map-like representation. The original instructions contain a verbal information format. Verbal information has certain notable characteristics: the representation is abstract, amodal, and relatively arbitrary, that is, words do not correspond in a natural, compulsory way to the objects, situations, or activities they refer to. Verbal elements are symbolic units, linked by overlearned, conventional associations (ie, the specific language adopted) to meaning and concrete referents in the world. Typically the information contained in verbal descriptions or instructions is thought to be based upon an underlying propositional network/representation.

Do we also possess information codes, which have a more direct spatial format? This question of course is reminiscent of the notorious imagery debate (Kosslyn, 1994; Pylyshyn, 1994). The central issue in this debate concerned whether knowledge representations are only propositional or instead may have a format more closely resembling the original perceptual inputs. Pylyshyn (2002) argued that the impression of possessing and inspecting (visual) mental images which are picture-like and intrinsically spatial of nature merely follows from us contemplating a nonspatial, propositional representation and deducing inferences from this representation on what the possible outside (physical and visuospatial) world could be. In contrast, proponents of a depictive knowledge representation theory claim that instead of single knowledge format (eg, propositional) we would also possess representations in the form of mental images. Mental images are presumed to have an analogue format. The analogue feature is typically interpreted by assuming that a representation is depictive and strongly comparable to the items in the physical world it represents. In consequence, analogue representations are presumed to be continuous (ie, properties of a representation may show a continuous variation rather than discrete steps) (Dretske, 1981).

In line with the foregoing, McCloskey (2001) differentiates between representations containing spatial information but in which the representation itself is not directly spatial and those which are intrinsically spatial to some extent. The instructions received from your friend could be an example of the former if you had kept them in purely verbal format in your memory. In contrast, in the latter case you would have converted the instructions into a more map-like format. Within this format one or more properties of the representation are isomorphic to the referent materials in the physical world (ie, distance of the streets you will pass through and orientations of the turns you need to take). Notice that the latter representations may differ in the extent of spatial correspondence or isomorphy. That is, you can construct either a more global, topological map, or a more metrically detailed topographic map. McCloskey (2001) further distinguishes mental representations in which the spatial properties of the representation are actually used to guide behavior and thinking from those in which they are contained in the mental representation but not used. Table 1.2 is a partial adaptation of Table 5.1 in McCloskey. We have chosen to ignore this last distinction but instead include a distinction between representations which contain limited isomorphy and those having isomorphy across multiple properties.

One of the concerns with depictive theories of mental images has been the question of who is doing the imagery. The metaphor often used is that of inspecting an image with one's mind's eye. The danger here is to assume some sort of homunculus who is interpreting the image. Related to this there is the question of whether images are necessarily conscious. A similar concern is linked to the three types of spatial representations described above. At the level of the neurons in the brain, none of the three representations is directly isomorphic to the outside world.[3] Hence we need a neurocomputational system to interpret and use the correlated patterns of neural activity to instantiate the functional characteristics associated with a particular type of spatial representation, either consciously or implicitly.

It goes beyond the scope of this chapter to address this interpretation stage here. Throughout this book we will entertain the idea that

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[3] The one exception could be retinotopic maps in the visual cortex corresponding in a one-to-one fashion with the visual stimulus patterns reaching the observer's eyes.

Table 1.2 Distinguishing between spatial contents of a representation and the extent to which a representation has a "real" spatial format

Format of spatial representation	***Criteria***	**Examples**
Spatial1	*The represented information is spatial. The representation itself is not spatially organized*	Verbal description of a route; digital clock time
Spatial2	a. *Spatially defined parts of the representation correspond to (spatial or nonspatial) parts of the represented material* b. *At least one spatial property defined over the parts of the representation is isomorphic to a (spatial or nonspatial) property defined over the corresponding parts of the represented material*	Subway map; family tree (indicating generations but not exact age differences)
Spatial3	a. *Spatially defined parts of the representation correspond to (spatial or nonspatial) parts of the represented material* b. *Multiple spatial properties defined over the parts of the representation are isomorphic to a (spatial or nonspatial) properties defined over the corresponding parts of the represented material*	Topographical map; 3D model of landscape or building

Adapted from McCloskey, M. (2001). Spatial representation in mind and brain. In B. Rapp (Ed.), *What deficits reveal about the human mind/brain: A handbook of cognitive neuropsychology* (pp. 101–132). Philadelphia, PA: Psychology Press (Table 5.1).

multiple representations of spatial information can exist in the human mind and brain. They will differ in how far their properties are isomorphic to characteristics of the outside world. In turn this raises the question of their efficiency for guiding spatial behavior. We will return to this when discussing disorders in spatial cognition and techniques to remediate these (see also chapter: Space in Neuropsychological Practice). See also Box 1.2 for a discussion of the cognitive map concept in representing the spatial world.

BOX 1.2 On the Origins of the Cognitive Map

One of the first scientific papers on mental maps of space was published by Trowbridge in Science in 1913 (Trowbridge, 1913). As the paper states its purpose was to address the "reasons why civilized man is so apt to lose his bearings in unfamiliar surroundings." The author identifies two basic methods for spatial orientation: the domicentered strategy which would be employed by animals, children, and uncivilized individuals, with strong reliance on the home base as point of central orientation; and the egocentric strategy available only to educated, civilized citizens and critically rests on the ability to align oneself with compass directions.

We may take this paper as one of the first scientific essays in which the idea of a mental map was entertained. This notion later received more extended and empirically inspired attention in the monumental paper by Tolman on the cognitive map (Tolman, 1948).

Tolman started with discussing the concept of latent learning in rats in a maze. Fig. 1.6 shows the maze in which rats were trained to find food in a goal location, starting from another place in the maze. One group of animals was always rewarded by food and learned quickly given the same start and goal location every day. Two other groups of rats were also included in the experiment. One group was not rewarded in the goal location until day 3.

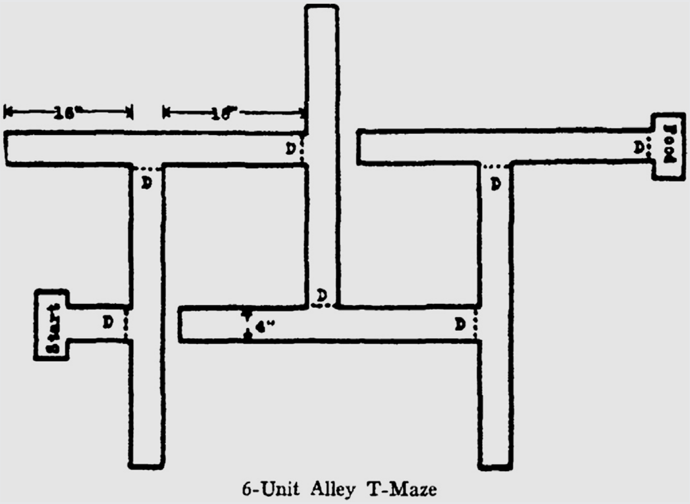

Figure 1.6 The maze discussed by Tolman in his paper on cognitive mapping in rats. *From Tolman, E. C. (1948). Cognitive maps in rats and men.* Psychological Review, *55(4), 189–208.*

(*Continued*)

BOX 1.2 On the Origins of the Cognitive Map—cont'd

The last group even had to wait until day 7 before they were rewarded in the goal location. As the (Figure 1.7) makes clear: the rate of learning was surprisingly high in the groups with delayed rewards in the goal location. Tolman took this as a sign that the rats engaged in some kind of spatial learning even when places in their environment did not contain any reward. Moreover, he argued that this spatial learning was not based on a chain of stimulus response associations, leading the animals from the start location to the goal location. Rather, he concluded that the rats gradually built up a field map or cognitive-like map of their environment. In a subsequent experiment Tolman showed that part of this map-like representation was a sense of direction.

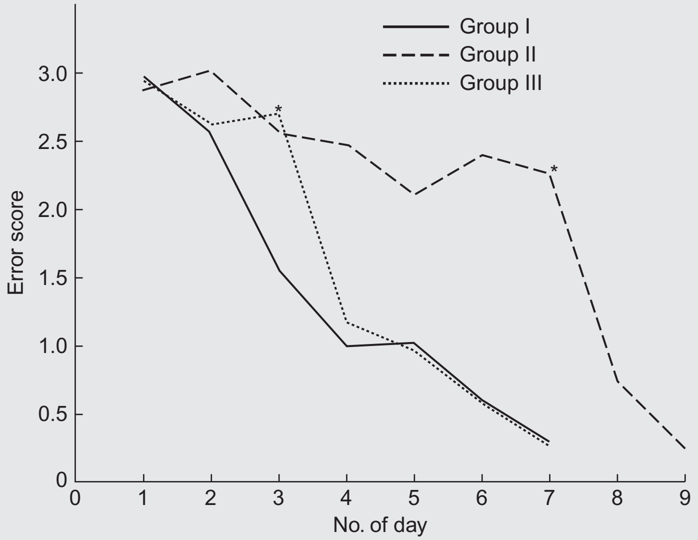

Figure 1.7 Maze performance by different groups of rats. *From Tolman, E. C. (1948). Cognitive maps in rats and men.* Psychological Review, 55*(4), 189–208.*

Tolman's notion of a cognitive map did not exclude the possibility that the rats' mapping system was based on an egocentric spatial reference frame or an updated egocentric representation. Without doubt the move towards a more allocentric interpretation of the cognitive map has been inspired by the monumental book by O'Keefe and Nadel offering an ambitious neurocognitive model of the cognitive map (O'Keefe & Nadel, 1978). O'Keefe and Nadel defended the existence of a representational system for absolute space "... a non-centred stationary framework through which the organism and its egocentric spaces move" (O'Keefe & Nadel, 1978). Functionally the idea was that the cognitive

(*Continued*)

BOX 1.2 On the Origins of the Cognitive Map—cont'd

map provides a Euclidean description of the surroundings from an allocentric reference perspective (cf. Burgess & O'Keefe, 2002), informing on places in the environment, objects to be found in that places, and spatial relations, driving wayfinding, goal-directed behavior and exploration. Importantly the cognitive map system allows one to locate oneself in a familiar environment and to go from one place to another even through parts of the environment never visited before.

The neural building blocks of this cognitive map system are thought to involve several circuitries in the hippocampal formation. Various spatially specific types of cells have been found in these parts of the brain, including place cells, head direction cells, grid cells, and boundary vector cells, allowing for absolute sense of place, allocentric direction, Euclidean distance, and closeness of environmental borders, respectively (Spiers, 2012). Whereas the foregoing cellular print of the cognitive map within the hippocampal formation has mainly been based on animal work, it seems to make sense to suppose that the human hippocampus and related structures contain cells with similar properties. A further discussion of the cognitive map concept can be found in Kitchin (1994).

The importance of the discovery of the neural basis of the cognitive map has been widely acknowledged (http://www.nobelprize.org/nobel_prizes/medicine/laureates/2014/press.pdf). In the field of human cognitive neuroscience it has been argued that the cognitive map system might have been crucial for the evolution of episodic memory, in particular by storing in memory the spatiotemporal contexts of episodes (Bird & Burgess, 2008). Episodic memory records the personal events of one's life. Retrieving an episodic memory is thought to require connecting multiple different elements of an event: what happened, when it happened, and where it happened (Tulving, 2002; or as described by Hassabis, Kumaran, & Maguire, 2007) integrating a sense of time and self, with semantic and sensory details, and visuospatial imagination. We may speculate that the ideal way to bring these elements together and create an episodic memory trace is in the absolute place holders offered by the cognitive map. Within these location representations the activities of the stored event can cognitively unfold. Bird and Burgess (2008) point out that the allocentric spatial map allows viewpoint shifts across stored scenes, and as such is essential for mentally replaying what happened during the original event linked to that scene and for episodic recollection. The cognitive map thus engraves an *eventscape* in our memories. (See Eichenbaum, Dudchenko, Wood, Shapiro, & Tanila, 1999 for a nonspatial interpretation of the role of the hippocampus in memory.)

1.4 DIVISIONS IN MENTAL SPACE

Whereas the space we move in seems to be a property of the outside world, which expands in a unitary continuous fashion, mental space has long been argued to break down in a number of qualitatively distinct subregions. A classical distinction is that between space close to the body and more distal space. Brain (1941) already noted distinct effects of superior and inferior parietal lesions on perceptual motor performance in grasping distance versus in walking distance. Comparative monkey studies further support the notion of qualitative distinction between processing near and far regions of space (Mountcastle, 1976; Rizzolatti, Matelli, & Pavesi, 1983). Grusser (1983) was one of the first to sketch an extended model of the distinct spaces surrounding ourselves within the world. He distinguished personal space from extrapersonal space; the former including the ego sense with the body and depending on the interoceptors; the latter containing several further subdivisions and depending on exteroceptors and motor systems.

A most elaborate model of the division of (mental) space has been offered by Previc (1998), dividing extrapersonal space in peripersonal (0−2 m from the body center), extrapersonal focal (0,2 m to distant space), extrapersonal action (2 m to distant space), and ambient space (most distant). Interestingly the Previc model contends that these spaces serve separate functions (going from grasping/reaching, to visual search and object recognition, to scene recognition and navigation, to postural control during locomotion), depend on different sensory inputs, engage different motor systems and reference frames/coordinate systems. In turn, distinct neural circuitries may be involved. Table 1.3 gives our own adaptation of the Previc model. In the original scheme extrapersonal action space only involved a gaze-centered reference frame. As we have argued earlier, however, allocentric referencing is critically involved in navigation. Interestingly gravitation is the prime reference system used in ambient space. We speculate that ambient vision and cues such as the sun's azimuth and pattern of polarized light in the sky[4] also support ambient space and in particular help us to globally orient in space (knowing what is up and down, and perhaps also cardinal directions such as north south). Recent work by Cardinali, Brozzoli, and Farnè (2009) has further specified body and peripersonal space in terms of body schema,

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[4] Polarized light in the sky is used by many insects for spatial orienting and apparently also by the ancient Vikings in the form of the so-called "sun-stones" (Ropars, Gorre, Le Floch, Enoch, & Lakshminarayanan, 2012).

Table 1.3 Spatial areas and their neurocognitive characteristics

	Spatial areas				
Characteristic:	**Body**	**Peripersonal**	**Extrapersonal focal**	**Extrapersonal action**	**Extrapersonal ambient**
Function	Posture; touch contact; pain; sense of agency; consumption	Multisensory space surrounding different body parts: hands, face, trunk, etc.; visually guided grasping; object manipulation	Visual search; object/face recognition	Navigation; scene memory; audiovisual target orientation	Spatial orientation; postural control; locomotion; long range navigation
Lateral extent	Front more than back; see Van der Stoep, Nijboer, Van der Stigchel, and Spence (2015)	Central 60°	Central 20–30°	Full 360°	Front 180°
Vertical bias	Depending on receptive fields body areas; see Longo, Mancini, and Haggard (2015)	Lower field	Upper field	Upper field	Lower field
Radial extent	0–0.5 m	0–2 m (reachable space depends on arm length); see Costantini, Ambrosini, Tieri, Sinigaglia, and Committeri (2010)	0.2 distance	2 m—distance	Very far
Primary coordinate/reference system	Body-centered	Body-centered (upper torso)	Retinotopic	Landmark-centered; environmental geometry	Gravitational; environmental geometry; stellar

					objects; polarized light
Sensory system	Somatosensory/ Proprioception; vestibular; gustatory; olfactory?	Visual (binocular); Somatosensory/ proprioception; vestibular	Visual (monocular)	Visual (monocular); auditory; olfactory; vestibular;	Visual (ambient motion, slant); vestibular; somatosensory/ proprioception
Motor system	Limbs and torso	Arm; smooth eye movements; head movements; saccades; leg kicks	Saccades	Head movements; saccades; upper-torso motion; leg movements	Leg movements; head movements
Neural correlates	Angular gyrus	Inferior parietal; dorsal stream; postarcuate frontal; cerebellum; globus pallidus; putamen; see also Aimola, Schindler, Simone, and Venneri (2012) for contrast with extrapersonal space	Inferior temporal; arcuate frontal; lateral intraparietal; Superior colliculus; caudate nucleus; lateral pulvinar	Superior + medial temporal; ventromedial frontal; posterior cingulate; hippocampal formation; auditory cortex; Superior colliculus; anterior thalamus	Parietal-occiptal; dorsal frontal; Ventroposterior thalamus; vestibular nuclei; cerebellum; putamen

Notice primary motor, sensory, and neural systems are given here, by no means intended to be a complete list.

Adapted from Previc, F. H. (1998). The neuropsychology of 3-D space. *Psychological Bulletin*, *124*(2), 123–164 (Table 1).

head- and hand-centered peripersonal space, and arm-centered reaching space. Chapter 5, Spatial Attention and Eye Movements, in the book deals mostly with personal and peripersonal space; Chapter 3, On Feeling and Reaching: Touch, Action, and Body Space, and Chapter 4, Multisensory Perception and the Coding of Space, are relevant for extrapersonal focal space; Chapter 8, Navigation Ability, addresses extrapersonal action and ambient space.

If the space we live in is mentally carved up in separate regions, and distinct modes of control at a perceptual, cognitive, motor and neural levels exist for different compartments of space, then it is likely that selective impairments can be detected after brain lesions. Indeed in particular for the disorder of spatial neglect double dissociations have frequently been reported between peripersonal and extrapersonal space (often labeled far space) (Berti & Frassinetti, 2000; Butler, Eskes, & Vandorpe, 2004; Keller, Schindler, Kerkhoff, von Rosen, & Golz, 2005; Van der Stoep et al., 2013). We will return to these selective disorders in Chapter 10, Space in Neuropsychological Practice. See also Box 1.3.

BOX 1.3 Historical Case of Spatial Disorder; Balint Syndrome

One of the first cases of a marked spatial disorder was recorded by Reszo Balint in 1909 (Balint, 1909). Balint (Figure 1.8) studied a patient suffering stroke followed by marked deficits in visual exploration. One particular symptom concerned the observation of neglect for stimuli in the left visual field. The anecdotal report describes that the patient was sitting on a bench looking straight ahead when the examiner approached him from the left but without evoking any reaction. In turn when the same procedure was repeated on the right side, the patient immediately detected the examiner (De Renzi, 1982, pp. 58–59).

Balint's patient suffered several additional symptoms of spatial impairments. An apparent inability to move his gaze once fixated on an object in the visual field to other elements in the visual world was most striking. Balint labeled this a psychic paralysis of gaze. Clearly this deficit had an impact on visual scanning behavior. A term coined somewhat later for this symptom is simultanagnosia: the inability to process multiple stimuli at the same time (see chapter: Multisensory Perception and the Coding of Space). A further symptom was disordered reaching and grasping. The patient could not produce adequate spatial actions upon target objects. For example, he lit a cigar in the middle and not at the end, and could not draw a simple (Figure 1.8) such as a triangle properly (De Renzi, 1982, pp. 59–60). This symptom was termed optic ataxia to denote severe impairment in visually guided motor action towards

(*Continued*)

BOX 1.3 Historical Case of Spatial Disorder; Balint Syndrome—cont'd

Figure 1.8 Reszo Balint.

objects (see chapter: Spatial Attention and Eye Movements). Postmortem neuroanatomical examinations revealed bilateral posterior parietal damage. The parietal circuitry since then became acknowledged as a particularly spatial circuitry, though its precise functionally has been open to discussion.

Why is the discovery of Balint syndrome so important for the neuropsychology of space? One reason lies in the fact that it has clear historical significance being one of the first documented cases with marked fall out in spatial domain whereas no clear degradation of cognition in other domains seems to exist. Throughout the following decades Balint syndrome has attracted scientific attention for various additional reasons. In particular there is the question of whether Balint syndrome should be regarded as a unitary syndrome or whether it is a complex of symptoms, which happen to vary over individual cases. Indeed symptoms often occur in isolation (Husain & Stein, 1988). If so there is the question of whether these symptoms are functionally linked and whether their co-occurrence is mediated by a single neurophysiological cause (see also Chechlacz & Humphreys, 2014). Clearly Balint's syndrome underscores the diversity of spatial cognition, composed of several more or less connected functional domains, similar to organization of this book.

See also:

http://www.frontiersin.org/Human_Neuroscience/researchtopics/The_enigma_of_B%C3%A1lint%E2%80%99s_syndrome:_complexity_of_neural_substrates_and_cognitive_deficits/1083

1.5 PHILOSOPHY OF SPACE

Given the historical importance of spatial concepts and the intrinsic complexities in both defining and measuring space, it will be no surprise that the concept of space has long dominated the philosophical debates. Actually several (sub)debates have been conducted about various, essential, spatial topics.

A most important topic concerns the question of whether space is absolute or relative. The absolute view states that space exists independently from the objects occupying it—space as such can be seen as a container. "Absolute space" would be like some substantial material of which any place is an "individual" because of some property. Objects occupy certain places because of the features of absolute space. The relative view in contrast holds that there are only objects and "space" is merely a name for the mutual relations between objects. Space as such can only be conceived because of the properties of the existing objects. "Relative space" in fact is literally nothing.

This particular debate became best known through the Leibniz–Clark correspondence (A Collection of Papers, which passed between the late Learned Mr. Leibniz, and Dr. Clarke, in the years 1715 and 1716; Collins, Clarke, Bulkeley, & Leibniz, 1717). Samuel Clarke strongly argued for Newton's notion of absolute space, whereas Leibniz considered this a nonobject. In his third letter Leibniz writes:

> As for my Own Opinion, I have said more than once, that I hold Space to be something merely relative, as Time is; that I hold it to be an Order of Coexistences, as Time is an Order of Successions. For Space denotes, in Terms of Possibility, an Order of Things which exist at the same time, considered as existing together; without enquiring into their Manner of Existing. And when many Things are seen together, one perceives That Order of Things among themselves.

Compare this with Newton's proposal of the absolute space concept in the *Principia* (Newton, 1687):

> Absolute, true and mathematical time, of itself, and from its own nature flows equably without regard to anything external, and by another name is called duration: relative, apparent and common time, is some sensible and external (whether accurate or unequable) measure of duration by the means of motion, which is commonly used instead of true time ... and Absolute space, in its own nature, without regard to anything external, remains always similar and immovable. Relative space is some movable dimension or

> measure of the absolute spaces; which our senses determine by its position to bodies: and which is vulgarly taken for immovable space…

And continuing, Newton argues:

> Absolute space, in its own nature, without relation to anything external, remains always similar and immovable. Relative space is some movable dimension or measure of the absolute spaces; which our senses determine by its position to bodies; and which is commonly taken for immovable space; such is the dimension of a subterraneous, an aerial, or celestial space, determined by its position in respect of the earth. Absolute and relative space are the same in figure and magnitude; but they do not remain always numerically the same. For if the earth, for instance, moves, a space of our air, which relatively and in respect of the earth remains always the same, will at one time be one part of the absolute space into which the air passes; at another time it will be another part of the same, and so, absolutely understood, it will be continually changed.

These are fully incompatible notions. Whereas modern physics might one day provide the ultimate solution, the present reader can easily appreciate the beauty contained in both views (see also Le Poidevin, 2003).

Linked to the question of whether space exists without objects and matter, another point of philosophical discussion is whether it is independent from the human observer, or in other words whether it is conceived as *ideal* or *real*. If *ideal*, it is subject-dependent, meaning depending on the (human) observer. If *real* it exists independently of the mind. Kant famously held that space is an a priori form of awareness, and is not real (Kant, 1781). In contrast modern mainstream science as well as analytical philosophy differentiate between "physical space" and "phenomenal space," and consider the latter a "representation" of the former. It is then suggested that biological fitness requires the representation to approach "veridicality," that is more or less fully matching with the former, "physical space." This renders physical space "real" but our mental representation possibly filled with gaps, or even distorted, but still having the possibility to support adaptive behavior in the world (cf. O'Keefe, 1993). In line with the latter, a major "constructivist" or "idealistic" undercurrent sides with Kant. It can be argued from ethology, especially Jakob von Uexküll's (Von Uexküll, 1909) work on the "Umwelt" of lower life forms, that an organism's "space" essentially equates with its "user interface." Since user interfaces shield the user from unnecessary complexity, they are typically not "veridical" at all. In that sense they are not fully "realistic," they are merely useful. O'Keefe argues that during evolution our brain has become tuned to order sensory inputs in an Euclidean interpretation of the physical world, even though the physical world is not organized in an Euclidean manner, because it offers direct survival value (O'Keefe, 1993).

Whether space is "real" and mentally represented in a more or less veridical manner or just a construct of the mind itself, the question remains how the mind's view on space is acquired. Are spatial concepts learned by sensory and behaviorally experiences or do we have an innate sense of space? The debate between nativists and empiricists has been going for ages with a peak in the 17th and 18th centuries. Kant argued that humans possess an innate, hardwired concept of space, which in turn would be one of the building blocks of human experience and knowledge. According to Kant: "*...Space is a necessary a priori representation, which underlies all outer intuitions. We can never represent to ourselves the absence of space, though we can quite well think it as empty of objects. It must therefore be regarded as the condition of the possibility of appearances, and not as a determination dependent on them*" (Kant, 1781; Wagner, 2006). In turn, empiricists argued that all our knowledge derives from our senses. In particular when mastering spatial concepts we would need to link motor actions (active touch) to sensory inputs (eg, visual perception). Box 1.4 addresses this last issue in more detail. Chapter 9, How Children Learn to Discover Their Environment: An Embodied Dynamic Systems Perspective on the Development of Spatial Cognition, explicitly deals with the development of spatial abilities and the way this can be disordered.

BOX 1.4 Molyneux' Question

In 1688 William Molyneux, philosopher, astronomer, and politician, wrote his colleague John Locke a letter in which he put forward the question of whether a person blind from birth could distinguish shapes by sight when by some intervention his sight was restored Fig. 1.9.

> Suppose Man born blind, and now adult, and thaught by his touch to distinguish between a Cube and a Sphere of the same metal, and nighly of the same bigness, so as to tell, when he felt one and t'other, which is the Cube, which the sphere. Suppose then the Cube and Sphere placed on a Table, and the Blind Man to be made to see: Quare, Whether by his sight, before he touch'd them, he could now distinguish, and tell, which is the Globe, which the Cube? (Molyneux's question)

(*Continued*)

BOX 1.4 Molyneux' Question—cont'd

Figure 1.9 *Figure copied from: Degenaar, M. (1989). Het probleem van Molyneux: een psychologisch gedachtenexperiment.* Kennis en Methode *(13), 131–146.*

Intriguingly this question directly addresses the ontology of knowledge and the nature of conceptual reasoning. Do we automatically appreciate and interpret incoming external information or do we have to learn it in a slow, incremental manner? The version of this question which has become publicly known limits itself to the apprehension of shapes and forms. While shape and form perception also includes a spatial dimension, it is of particular relevance for our discussion on the origins of spatial thought that originally Molyneux did include a further formulation:

> . . . A Man, being born blind, ...suppose his Sight Restored to Him, ...Or Whether he Could know by his sight, before he stretched out his Hand, whether he Could not Reach them, tho they were Removed 20 or 1000 feet from him?
>
> ***(Degenaar, 1996; Jacomuzzi, Kobau, & Bruno, 2003)***

Interestingly, Molyneux' problem has not only initiated substantial philosophical discussion, but it has also inspired several empirical investigations (see also Wade & Gregory, 2006). Most of them have focused on the scarce cases of successful sight restoration in the ages following the formulation of the problem, typically after cataract operations. Due to

(*Continued*)

BOX 1.4 Molyneux' Question—cont'd

methodological limitations none of them has succeeded thus far in fully proving or discarding either the nativist or empiricist point of view. Still the question remains very intriguing as to whether we possess some innate ability to organize incoming sensory information in a truly spatial way or whether either a rapid or slow experience-based learning process is required. Modern neuroimaging research might provide a new line of discovery into this old question regarding the ontology of (visuo)spatial knowledge. Levin, Dumoulin, Winawer, Dougherty, and Wandell (2010) showed that in a man who had regained sight after 43 years of darkness structural changes in the visual cortex persisted even after 7 years of sight recovery, including enlarged population receptive field sizes and reduced longitudinal diffusivity in the optic track. Behaviorally this was accompanied by poor spatial resolution, monocular depth perception, and perception of illusory contours, against excellent motion processing (Fine et al., 2003). Together these results may indicate a critical period in life during which neural plasticity is high and several perceptual skills including spatial information processing have to be acquired, while at the same time some perceptual qualities (eg, motion) appear robust and hardwired, both neutrally and cognitively. A mixed yes/no to the question raised by Molyneux?

The quest to solve the nature of space (and time alongside it) has been of utmost significance for the progress of philosophy and science as well. The foregoing pages have only addressed a selection of central philosophical debates underlying this quest in a very cursory manner. For our exploration of psychological space (and the neuropsychological ailments that torture it) we are inclined to follow a pragmatic approach. Is space absolute or relative? Cognitively we can easily think about empty spaces or distances and space as a sort of container. Our memory for a certain place might improve over multiple learning episodes even though each day it is occupied by a different object. In contrast moving objects to new places might cause interference (see chapter 7: Keeping Track of Where Things are in Space—The Neuropsychology of Object Location Memory). On the other hand, the importance we have placed on the notion of reference frames, if anything, sides with a more relative view of space. Is space real or ideal? While acknowledging the complex relation between physical and mental/psychological space, for our daily functioning and survival in the world it would best to attribute some sort of reality to (physical) space. Is our sense of space innate or depending on critical learning periods and experiences? For the neuropsychological purposes of this book we intend to shed light on both innate constraints to process spatial information and on discovering which types of training programs might be best for development, education, and rehabilitation. A closing thought might be that one day training in special VR environments might help us to conceive of more than just three spatial dimensions.

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