Journal of Experimental Psychology:
Human Perception and Performance
2004, Vol. 30, No. 5, 907–912

0096-1523/04/$12.00 DOI: 10.1037/0096-1523.30.5.907

Analysis of a Constraint on Perception, Cognition, and Development: One Object, One Place, One Time

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It has become increasingly common for theories to rely on a constraint that 1 object cannot be in more than 1 place at the same time. Analysis suggests that a 1 object–1 place–1 time constraint as literally stated is false, that a modified constraint is biased toward the visual modality, that it may not be a correct description of the physical world, is not true of how objects must appear on sensory surfaces, and does not mean that 2 simultaneous spatially separated samples must be interpreted as 2 different objects, even for vision. However, once such object numerosity or identity is determined in some other way, then a modified constraint can be used to trigger learning, such as prism adaptation. A far-removed implication is that "Where is an object?" may be a misleading question.

A number of psychological theories assume that one object cannot be in more than one place at one time. For instance, in attention theories, "object files" (Kahneman, Treisman, & Gibbs, 1992) are created on the basis of location. Similarly, "indexes" (Pylyshyn, 1989, 1994) are assigned and accessed by location. In both theories, entities in two locations at the same time get two distinct object files or indexes, one for each location. The assumption is even more prominent when location-based theories are extended to infants' perception of objects: "Because objects are indexed by location, seeing two objects in different locations at the same time forces the assignment of two indexes: therefore two individual objects are inferred" (Leslie, Xu, Tremoulet, & Scholl, 1998, p. 15). Other researchers have been explicit that adult (e.g., Bedford, 1993a, 1993b, 1995, 1999) and infant (Narter, 1998; Rosser, Narter, & Paullette, 1995; Wilcox, Nadel, & Rosser, 1996; Xu & Carey, 1996) observers possess a constraint that one object cannot be in two places at the same time:

> Spatiotemporal criteria are constraints on how physical objects can and cannot exist and move in time and space. For example, one object cannot be in two places at the same time, [and] two objects cannot be in the same place at the same time. (Narter, 1998, p. 70)

In developmental work generally, two entities that appear in two places simultaneously allow infants to conclude that there are two objects, not one. A one object–one place–one time rule may be a subset of the law that objects must travel on continuous paths in space and time (cf. Spelke, 1991). Such spatiotemporal regularities are viewed as the most fundamental of truths and the primary means that even infants have at their disposal for individuating a complex scene (Spelke, 1991; Spelke & Hermer, 1996).

However, is the constraint the universal truth that it is assumed to be? First, the proposition as stated is, strictly speaking, *false*. Not only can one physical object be in more than one place at one time, it must be. The tip of a pen and the base of that same pen are in two places at the same time. Likewise for any two parts of any one object, no matter the nature, size, or nearness of the parts. The only entity that does not have this property is an abstract point, which as Euclid defined, is that which has no part. Physical objects extend in space. Each one must occupy multiple spatial positions simultaneously or it is not an object. This is true even if *part* is problematic, a term that comes with preexisting biases; *matter*, *multiple points*, or *extent* can be used instead. Thus, the constraint as stated is casual shorthand for, at minimum: One *point* on an object cannot occupy more than one place at one time (as in Marr, 1982). I return to this seemingly trivial change at the close.

Moreover, even with the correction, the constraint may not be a general regularity for sorting the sensory array. It is biased toward *vision*, as theories often are. Michael Kubovy (1981; see also Kubovy, 1988; Kubovy & Van Valkenburg, 2001) has shown how different modalities have different attributes that are indispensable for determining numerosity. In his theory of indispensable attributes, space is used for enumeration in the visual modality. Two patches separated by a spatial gap but otherwise identical indicate two *objects*. In *Through the Looking-Glass* (Carroll, 1871), Tweedledee and Tweedledum are counted as two people, not one, even though they seem identical in all regards save for spatial separation (see also Lucas, 1973). However, critically, space is dispensable for audition. Kubovy continues with two sounds coming from two spatially separated speakers. If the speakers play the identical sounds with the same pitch (frequency), observers hear one stimulus, not two, despite the spatial separation. It is only when the two sounds have different pitches that observers individuate two "objects," say both a violin and a flute. Even if the two pitches are in the same location, two distinct objects are discerned. It is pitch that is indispensable for numerosity in audition; space is irrelevant. If space is irrelevant for determining numerosity in audition, then a single "auditory object" (Kubovy & Van Valkenburg, 2001) can be in one, two, or a dozen locations simultaneously and still be one single object as long as it has one pitch. Kubovy's theory of indispensable attributes suggests then that one object can be in more than one place at one time in audition.

Does this in turn suggest that if our constraint is restricted further by modality, it is now accurate? *For vision*, (one point on) an object

Thanks go to Merrill Garrett, Thomas Bever, William Ittelson, and Michael Kubovy for illuminating discussions. This work was supported by a grant from the Social and Behavioral Research Sciences Institute, University of Arizona.

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cannot be in more than one place at the same time. Unfortunately, the seemingly intuitive claim is problematic for vision as well. While Tweedledee and Tweedledum may be different people (Kubovy, 1981; Lucas, 1973), Groucho wasn't so sure that Harpo was separate from himself in the movie *Duck Soup* (Mankiewicz & McCarey, 1933). Harpo mimicked Groucho's every move. When one image went left, so did the other; when one shook his leg, so did the other; when one picked up a cane, so did the other. There was a spatial separation, but identity otherwise. Was Harpo a different person with a different count, or was he merely Groucho seen through a mirror? One (point on an) object reflected by a mirror can appear to be in two places at the same time. I have two identical collie figurines spatially separated from one another and also near a mirror. When my eyes sweep by the display quickly, I cannot tell with certainty how many collies there are—sometimes it looks like two, but other times only one, and other times four distinct individuals. In addition to mirrors, observers with "double vision" (diplopia) will experience a single (point on an) object as occupying multiple positions because the eye muscles are sufficiently weak as to prevent fusion of the two retinal images into a single image. Another example is a nearsighted eye that leads to a blur circle; that is, one point in the world produces several points on the retina because the lens–eyeball mismatch focuses the image to a single point in front of the retina rather than on it. Consequently, two spatially separated samples in vision, otherwise identical, do not guarantee that their origin is two distinct objects in the physical world.

However, perhaps mirrors, diplopia, and nearsightedness are precisely circumstances in which observers infer two objects from two visual samples too often, even if it produces erroneous perception. Someone with double vision may report seeing four fingers and not the two that were really put before his or her eyes. Someone who hasn't noticed a mirror may try to walk through to the "objects" on the other side. A mirror causes the appearance of one point in two places simultaneously, but will the two points really be *interpreted* as only one object?

It is clear that distinctions need to be drawn as to what precisely a constraint about one time, one place, one location is supposed to refer to. At least three meanings can be distinguished. Any theory that makes use of the constraint must, at minimum, be explicit about which meaning is intended. Is the constraint a statement about *reality*, referring to what is true of the physical world apart from our interactions with it? Is it a statement about *appearance* or the mapping from the physical world to the sensory arrays?: How do the objects we believe to exist in the physical world appear at the sensory surfaces of different modalities? Or does the constraint refer to psychological *interpretation*?: What inferences does the mind draw from the sensory information about the state of the world, and how does it do so? The constraint as used in the literature can touch on all three meanings. It reflects a belief that the constraint describes reality; that is, we claim objects behave in certain ways independent of our experience of them. In addition, it appears to be a claim that we possess an equivalent constraint psychologically. The psychological constraint may have resulted from *internalization* (Shepard, 1984) of the physical constraint through natural selection if it produced a survival advantage and reflected a truth that was stable throughout our evolutionary history (Shepard, 1984, 2001). This duplicate constraint, presumably along with assumptions about the rules of appearance, is used to interpret the sensory information.

Yet the different categories can be logically distinguished. For Appearance, we have seen that the constraint is false, such as when the visual image of an object has a mirror twin. For Reality, is the constraint that one (point on an) object cannot be in two places at the same time a correct description of the behavior of objects in the world? Putting aside that we have not defined *object*, if what we mean by *place* is a holder for a point in the spatial medium, then the constraint may say that one point cannot be two points, which is more of a tautology than a constraint. Does this actually describe the behavior of a point or what it means to be a point (see also Bloom, 2000)? But this is more of an abstract analysis than a physical one. For the physical world, physicists do tend to believe that bits of matter occupy distinct and definite physical locations. However, in quantum theory, a single component at a very small scale can in fact exist in different locations simultaneously. As a description of the physical world, then, the constraint is either obviously true, or it is false.

If the constraint need not be true of appearance, and may or may not be true of the physical world, is it at least true of interpretation? Psychological interpretation of the sensory array is arguably the category of greatest consequence in perceptual and cognitive theories. To return to the issue raised by walking through mirrors, must two simultaneous spatially separated samples involving vision be *interpreted* as two objects?

No. A counterexample is provided by *prism adaptation*, a phenomenon that would not occur without an interpretation of one object given to two spatially separated simultaneous samples (Bedford, 1995, 1999, 2001; Welch, 1972). When observers look through a prism, the visual image of the world appears laterally displaced from where it really is. A (point on an) object that is grasped will appear to be in one position through vision but in a different position through touch. The spatial discrepancy leads to adaptation (e.g., Wallach, 1968; Welch, 1978), in which one modality will change to realign with the other. However, it has been demonstrated both empirically (Welch, 1972) and logically (Bedford, 1993a, 1999, 2001) that adaptation will not occur unless the differing location signals are believed by the observer (not necessarily consciously) to originate from one object. The mere localization of two places at one time, even when it happens that one is localized through vision while the other through proprioception, is not enough to produce change because two points on two objects are often in two places. It is only if those two places are interpreted to refer to (one point on) one object that there is a genuine discrepancy from expectation, which can lead to the detection of an internal error and its subsequent correction through the process we know as prism adaptation.[1] Bedford (1993a, 1993b, 1995, 1997, 1999) has argued that no functionally adaptive change in perception can occur until the sensory information indicates an error in the sensory systems themselves. Prism adaptation may be

[1] Bedford (1999) described three possible reactions that an observer can have to a "discrepancy" between localizing a hand in one place and seeing it in another and added a fourth in a later work (Bedford, 2001). The differing values from the two modalities could indicate that (a) one hand can be in two places at the same time, which would be a fact about the world ("oh wow"); (b) one of the observer's sense modalities is providing erroneous location information, because the observer knows that what he or she is detecting is not possible ("uh oh"); (c) there are just two different hands, one in each position ("ho hum"); or (d) there is one big hand that extends through both positions, and the observer is detecting a different part through each modality. The second conclusion is required to get an internal perceptual change that involves a shift in seen or felt locations (adaptation).

essential to keep perception accurate in the face of mismatched growth in childhood and random drift in adulthood (Held, 1955, 1965; Howard, 1982). However, adaptation could not occur were it not that the appearance of two different positions simultaneously is interpreted as (one point on) one object, not two objects. The existence of prism adaptation shows that two entities in two places not only can be caused by one object objectively, but they can also be interpreted as one object by the observer.

The counterexample to a one object–one place–one time constraint provided by prism adaptation raises two questions. First, didn't I just sneak back the very constraint as an argument against the constraint? Prism adaptation is error correction, which will only occur if one point on one object appears to be in two places simultaneously, which indicates an error with one of the modalities because we all know that *one object can't be in more than one place at one time!* The difference in usage of a constraint is one of processing level. In addition to distinctions among constraint categories of Reality, Appearance, and Interpretation, there are further distinctions that need to be drawn among levels of processing at which the constraint could operate within the category of Interpretation. An important level concerns the use of spatially separated samples to draw conclusions about numerosity. As the example from prism adaptation shows, if there are two spatially discontinuous samples at the sensory array at the same time, they will not necessarily be processed as two numerically distinct objects. This claim appears to contrast with developmental theories of the object concept in infants[2] and object-based attention theories in adults. It is consistent with the theory of indispensable attributes in perception if spatial separation does not ever force an interpretation of multiple objects.[3] In general, the presence of two simultaneous spatially separate stimuli is not a sufficient criterion to individuate objects or automatically open separate object files. However, the counterexample of prism adaptation also suggests that should it be decided by some *other* criteria that two discontinuous samples at sensory surfaces do refer to one object, then this one-object conclusion will violate expectation at a later processing level.

The second question raised concerns whether the constraint is really contradicted in circumstances involving *only* vision. Prism adaptation is based on information obtained from more than one modality. As seen earlier, space is not an indispensable attribute in audition as it is for vision. For proprioception (touch), it is not clear what the indispensable attributes are. If space is dispensable for proprioception too, then getting the one-object interpretation from multiple spatial locations may require that either this modality or audition be involved. What about cases in which the only modality involved is vision?

In addition to looking through mirrors, when double images are often correctly interpreted as referring to single objects, consider two simultaneous spatially separated points. They can be processed as one object, and often are. This is precisely what the classic Gestalt grouping principles (Wertheimer, 1923/1938) are about—discerning how many objects are responsible for the sensory array of discontinuous points: "I stand at the window and see a house, trees, sky. Theoretically, I might say there were 327 brightnesses and nuances of colour. Do I *have* '327'? No. I have sky, house, and trees" (p. 71). Two discontinuous points can refer to the same object via the classic principle of *proximity* when they are closer to each other than to any other points in the display. *Common fate* would also link the two points, even if they were far apart. The principles work because we can work backward from the sensory array to reconstruct properties of objects and how they map onto us; points on an object tend to be near one another; points on an object tend to move together at the same time and rate. The two points do not necessarily refer to one *point* on one object, but they refer to one *object* nonetheless, the level of analysis that theories on object identity are typically concerned with.

Analogously, one-object interpretations apply not only for individual points but also for spatially extended samples, such as 2-D closed figures or 3-D bounded solids. Consider viewing two fingers simultaneously with a gap between them without seeing what they are connected to. If they move in synchrony, an observer will be more likely to conclude that they belong to one hand, not two, than if they did not have common fate. But one may argue that there are still two *fingers*—that the spatial gap automatically implicates two objects of some sort, even if the objects are on a smaller scale. Now consider two samples that consist of what appear to be the left edge of a finger and the right edge of a finger but with nothing between them except empty space. Can they refer to one finger despite the gap? Yes. Perhaps the finger is painted with a chemical that causes invisibility in those regions, or perhaps a visual deficit prevents some retinal signals from further processing. Philosophers are fond of talking about bipartite objects. (For a recent philosophical discussion of parts and wholes and their relation to space, see, e.g., Casati & Varzi, 1999, especially chap. 6.) But what about the interpretation of such a display? We know from the phenomenon of apparent motion that a missing signal on the retina is not an insurmountable obstacle to inferring one object; two stimuli alternating in two different positions are interpreted as one object moving back and forth, even with the missing retinal information in between (Rock, 1983; Shepard, 1984). There is no reason that two simultaneous stimuli in two different positions with a gap between them cannot be interpreted as one finger.

But aren't there still two *somethings*, even if the conclusion implicates one finger? Yes and no. I refer above to viewing two

[2] Note the potential confusion of level in the Leslie et al. (1998) quote reproduced earlier: "Seeing two objects in different locations at the same time forces the assignment of two indexes: therefore two individual objects are inferred" (p. 15). If this refers to the interpretation of the sensory array in order to individuate objects, then the statement is incorrect, but the statement is unclear because observers would not need to individuate objects if they already were seeing *two* objects.

[3] The original theory of indispensable attributes (TIA; Kubovy, 1981) may have appeared to some readers to imply that spatial separation *must* be used to enumerate objects in vision. However, recently it has been clarified (Van Valkenburg & Kubovy, 2003, p. 230, section 3.1; see also Kubovy & Van Valkenburg, 2001, p. 108, last paragraph) that in TIA, separation in the indispensable attribute does not, in fact, ensure enumeration, only makes it possible. Note that an essence of TIA is not affected: The role that space–time plays for enumeration in vision is analogous to that of pitch–time in audition. Recently, Neuhoff (2003) has challenged the TIA and argued that pitch is neither necessary nor sufficient for enumeration in audition (but see Van Valkenburg & Kubovy, 2003). The sufficiency claims may be analogous to the present claim concerning space in vision, but both "challenges" taken together seem to strengthen rather than weaken the TIA. Space in vision plays the same role as pitch in audition, and in neither modality is enumeration based on its respective indispensable attribute obligatory. Rather, the same two samples may refer to one object in one circumstance but to two *objects* in another circumstance (Bedford, 2001).

samples. What governs that they should be referred to as *two* samples and not one? The answer is that discontinuities can determine samples: Whenever anything is different, there are two samples. This suggests that there is an additional level of interpretation at the input for which a constraint about one object, one place, one time could be referring to in psychological theories. Two discontinuous points in space (i.e., two points with a spatial gap) indicate, of necessity, two samples, but not of necessity two objects. The question of theoretical interest is usually whether or not those two distinct *samplesomethings* refer to distinct *objectsomethings*.

So, is there or isn't there a constraint for vision that (one point on an) object cannot be in more than one place at one time? To summarize: *no* for Appearance, *unclear* for Reality, and for issues of Interpretation, the question needs to be asked separately for at least three processing levels. At the input for Interpretation, spatial discontinuity determines how many samples there are. But there is nothing special about spatial discontinuities that would warrant a constraint. A discontinuity in time also determines different samples. Two spatially separated points or entities that are *not* simultaneous also produce two samples, as do two samples that are in the same place and not simultaneous. A constraint at this level would not be meaningful. At the next level of determining whether two samples defined by discontinuities do or do not refer to the same object—the issue known as *numerical* or *object identity* (e.g., Bedford, 2001; Leslie et al., 1998; Meltzoff & Moore, 1998; Xu & Carey, 1996)—the constraint is false. Two samples do not automatically imply two objects—that is what must be decided. Analysis of the constraint suggests that *whenever there are two samples, regardless of whether they are simultaneous or from different times, regardless of whether they are from vision, from audition, or a combination of modalities, and regardless of the size of those samples, the observer must ask whether they refer to one object or two objects*. Two simultaneous separated samples in any modality can be interpreted to refer to the same object. A whole set of criteria is needed to resolve identity. But once an object identity decision is reached, then at a third level, we do have an expectation: If it is one physical object, each point on that object will occupy a definite and unique position. If information on sensory surfaces indicates otherwise, then there is a violation of expectation. Expectation or surprise leads to learning. At that third level, then, we *do* have the constraint.

Before concluding, note it is clear that constraints need not be propositions or rules that are "applied" but rather built in the architecture (e.g., Marr, 1982; Munakata, McClelland, Johnson, & Siegler, 1997; O'Reilly & Johnson, 1994; see Spelke & Newport, 1998, for discussion). Yet Paul Rozin and Jonathan Schull (1988) remind us that we would not say that birds are constrained to fly! What we mean by a constraint on perception and cognition, even if it is built into the architecture, and whether it affects phenomenological perception or cognitive beliefs or both, requires further explication.

Note also that distinctions drawn here may help solve a puzzle concerning constraints and evolution. Roger Shepard (1984, 2001) has argued that facts about the world that are general, have been stable throughout our evolutionary history, and convey a survival advantage over having to learn them through "trial and possible fatal error" (Shepard, 1984, p. 418) will become internalized as constraints that affect perception and cognition. Yet why does something that is general and true need an a priori constraint? That should be the very type of truth that is easiest to learn about (R. Shepard, personal communication, 1995). I suggest that it is when the *appearance* of something varies and can conflict with reality that a constraint is useful. If one point on one object always appears in one place, there may be no need to have a constraint that represents this at any level; we would "discover" it soon enough. But suppose, for example, that physical growth affects different modalities at different rates (see Banks, 1988; Bedford, 1999; Held, 1965); then, one point on one object will appear in two places simultaneously when surveyed by the two modalities. Were it not for a constraint that this should not occur despite appearances, we would draw a very different, likely inaccurate, conclusion about the physical properties of entities in the world.

Finally, I return to the first point. Is the correction that it is (*one point on*) the object that cannot be in two places at the same time simply an obvious and picky technicality? First, it should raise the issue of whether *objects* are critical to the constraint—one point (*on an object*) cannot be in more than one place at the same time. More important, it draws attention to imprecise usage of the idea *the location of objects*. Objects do not have locations, points do. One popular misuse may be the distinction between "What is the object?" (dorsal stream) and "Where is the object?" (ventral stream), a division (Mishkin, Ungerleider, & Macko, 1983) that has been well known and accepted until recently. "Where is the object?" is shorthand for idealizing the object as a point source and asking, "Where is the point?" Consequently, a candidate for a major division in perception may be more one of processing a single point versus an extended contour, a distinction drawn more than 30 years ago by Richard Held (1970), than of "where" versus "what" or even "what" versus "how" (Goodale & Milner, 1992). Once there are spatial extents, as in visual objects, there may not be any hard division between location information and other geometric properties when observers process those objects (Bedford, 2001).

Conclusion

I have claimed that an alleged one object–one place–one time constraint may not be true of the physical world, is not true of how objects must project to sensory surfaces, and perhaps most important, does not prevent observers from perceptual interpretations that violate the "constraint." This is most apparent with Kubovy's (1981; Kubovy & Van Valkenburg, 2001) examples from audition, in which spatial separation is never used to enumerate objects, but is also true of cross-modal perception and of vision. For cross-modal perception, prism adaptation shows that visual and proprioceptive samples in different locations at the same time are nonetheless interpreted as referring to a single object, and in vision, part–whole Gestalt relations and mirror perception provide counterexamples to the constraint. Additional counterexamples will likely be found empirically now that it is apparent that there exist violations of interpreting sensory information in accordance with a one object–one place–one time rule.

An important implication of the analysis is that any theoretical framework is wrong if it assumes that simultaneous spatially separated patches–entities–stimuli must be interpreted by observers as indicating two distinct objects. This appears to include the increasing body of adult and infant work that rests on automatically assigning distinct indexes, object files, and objects on the basis of spatially separated samples. It is a question for theoretical

and empirical research of how, whether, and under what circumstances two samples, whether they are within or between modalities, simultaneous or successive, will be determined by an observer to refer to one or two objects (object identity as broadly defined; see, e.g., Bedford, 2001, Xu & Carey, 1996); it is not a matter of assumption. Also open for exploration is how following such an object identity determination, discrepancies between the number of inferred objects and the number of counted positions can be used to drive learning. It is at this level that a constraint that (one point on) one object cannot be in more than one place at one time has the greatest promise—perhaps as a constraint on learning rather than perception. A tangential implication is based on the clarification that although localization of an individual point is sensible, whenever there is spatial extent, location is fundamentally intertwined with other geometric properties. Any singling out of "Where is an object?" from the more general "What is an object?" is likely to be erroneous. In any event, all perceptual, cognitive, and developmental theories that make use of a one object–one place–one time constraint (either implicitly or explicitly) should reexamine and be explicit about what categories and levels the constraint is referring to and reevaluate conclusions based on its use.

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Received August 1, 2003
Revision received March 22, 2004
Accepted March 29, 2004 ■