In: Killeen, P. R. & Uttal, W. R. (Eds.) (1999). *Fechner Day 99: The End of 20th Century Psychophysics. Proceedings of the Fifteenth Annual Meeting of the International Society for Psychophysics*. Tempe, AZ, USA: The International Society for Psychophysics.

HOW CONSEQUENCES OF PHYSICAL PRINCIPLES INFLUENCE MENTAL REPRESENTATION: THE ENVIRONMENTAL INVARIANTS HYPOTHESIS

Timothy L. Hubbard
Texas Christian University

Abstract

The environmental invariants hypothesis suggests that (a) mental representations automatically extrapolate effects of invariant physical principles on the referent physical objects, and (b) the results of this extrapolation distort spatial memory. The extrapolations preserve a second-order isomorphism between the dynamics and kinematics of physical objects and the mental representations of those objects, and such an isomorphism has implications for theories of cognitive structure and processing across a variety of domains.

The remembered position of a target is usually displaced from the actual position of that target, and the pattern of displacement is often consistent with the operation of invariant physical principles on that target (for review, see Hubbard, 1995b). For example, an observer's memory for the final location of a horizontally moving target is displaced forward and downward, and this pattern is consistent with the operation of momentum and gravity on such a target. Several different types of displacement in spatial memory have been documented, and these displacements may reflect nonconscious or implicit knowledge of environmentally invariant physical principles that has been incorporated into the functional architecture of the representational system (Hubbard, 1998a).

Types of Displacement

Representational Momentum

If an observer views a target undergoing either implied or apparent motion, and that target vanishes without warning, then that observer's memory for the final position of the target will be shifted forward slightly in the direction of motion (see Figure 1). Freyd and Finke (1984) referred to this forward shift as *representational momentum*, and they suggested that it resulted from an internalization of the principles of physical momentum by the representational system; much as a moving physical object cannot be immediately halted because of its momentum, the mental representation of that motion cannot be immediately halted because of an analogous momentum within the representational system. More recently, Freyd (1987, 1993) suggested representational momentum reflected a spatiotemporal coherence between the represented and representing worlds, and Hubbard (1995b) suggested representational momentum (and other displacements arising from environmentally invariant principles) combined with other factors (e.g., memory averaging, observers' expectations) to determine the ultimate distortion in the remembered position of a target.

Representational Gravity

Memory for a descending target exhibits greater representational momentum than does memory for an ascending target, and memory for a horizontally moving target is also displaced downward below the path of motion (for review, see Hubbard, 1995b). These patterns are consistent with the effects of gravity on a moving physical target (i.e., descending targets accelerate, ascending targets decelerate, and [unpowered] horizontally moving targets fall along a parabola) and the existence of *representational gravity*. Also, target size influences displacement only along the axis aligned with the direction of implied gravitational attraction (Hubbard, 1997, 1998b); effects of target size may be limited to the axis aligned with implied gravitational attraction if the representation of the target is sensitive to the weight, and not the mass, of the target. Such an interpretation is consistent with the size-weight illusion and with previous findings that observers are sensitive to the implied weight in visually perceived or imagined stimuli.

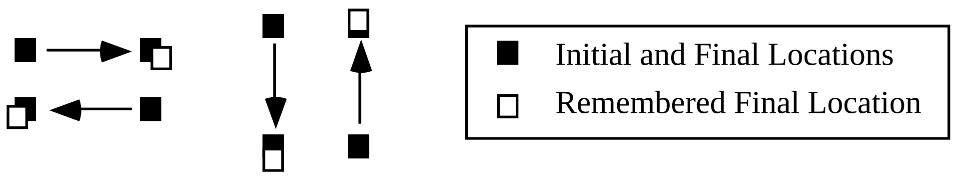

Figure 1. The relationship between actual and remembered final locations of horizontally and vertically moving targets. Targets move smoothly from initial to final location, and then vanish (without warning) at the final location. After targets vanish, subjects indicate the remembered final position. Representational momentum is shown by the forward displacement of remembered location; representational gravity is shown by the downward displacement of horizontally moving targets and by the larger forward displacement for descending motion than for ascending motion. Arrows indicate the direction of motion. Adapted from Hubbard (1998a).

Representational Friction

When a horizontally moving target crashes through a barrier, forward displacement is decreased, and larger decreases are observed with larger barriers (Hubbard, 1995a). When a horizontally or vertically moving target slides across one or two larger stationary surfaces, forward displacement decreases as the number of contact surfaces increases (see top of Figure 2); when a horizontally moving target moves along a surface and compresses the surface behind it, displacement decreases even more (see bottom of Figure 2; Hubbard, 1995a, 1998b). Given that increases in physical friction produce decreases in physical momentum, these patterns are consistent with the existence of *representational friction*. Memory for a target is displaced downward along an inclined plane when the slope of the plane is steep, but not when the slope of the plane is shallow (Bertamini, 1993); this may reflect a combination of representational friction and representational gravity (i.e., a physical object is more likely to slide down an inclined plane as the slope increases and gravity becomes stronger than friction, and so memory is more likely to be displaced down an inclined plane as the slope increases and representational gravity becomes stronger than representational friction).

Representational Centripetal Force

When a target moves along a circular orbit, memory for the location of the target is displaced forward and inward (Hubbard, 1996b). Forward displacement (when measured in pixels along the tangent) increases with increases in either angular velocity or radius length, and inward displacement increases with increases in angular velocity and radius length (see Figure 3). Given that circular motion is specified by forward momentum along the tangent (reflecting the direction of motion in the absence of the constraint to circularity) and by inward centripetal acceleration toward the focus of the orbit, this pattern is consistent with the existence of both representational momentum and a *representational centripetal force*. Freyd and Jones (1994) presented targets that traveled through a spiral tube and then followed either a spiral, curvilinear, or straight path after exiting the tube. Displacement along the path of motion was largest along the spiral path and smallest along the straight path, and this pattern is also consistent with an interaction of representational momentum and representational centripetal force.

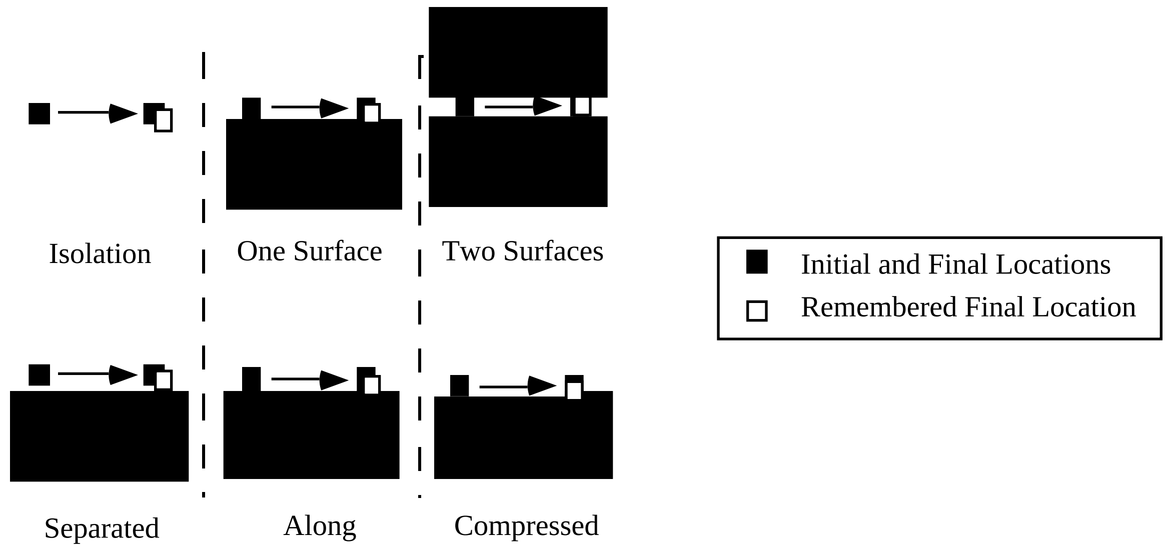

Figure 2. The top panel illustrates effects of implied friction on displacement for targets presented in isolation, sliding along one surface, or sliding between two surfaces. The bottom panel illustrates effects of implied friction for targets separated from a surface, sliding along a surface, or compressing a surface. Targets move smoothly from initial to final location, and then vanish (without warning) at the final location. After targets vanish, subjects indicate the remembered final position. Representational friction is shown by the decreases in forward displacement with (a) increases in the number of surfaces contacted by the target and (b) increases in the implied contact with (and pressure on) a surface. Arrows indicate the direction of motion. Adapted from Hubbard (1998a).

Environmental Invariants Hypothesis

The *environmental invariants hypothesis* proposes that physical principles invariant across our experience (e.g., momentum, gravity, friction, centripetal force) have become incorporated into our representational system. Therefore, our representational system responds as if the mental representation of a physical object were subject to the same physical principles that influence that physical object.* The incorporation of invariant physical principles takes the form of an automatic extrapolation in which mental representation is biased in ways consistent with the operation of those physical principles; this bias typically takes the form of a displacement between the remembered position of the target and the actual position of that target. Of course, mental representations of physical objects would not actually be displaced within the coordinates of the brain; rather, the "as if" nature of the displacement is suggestive of a second-order isomorphism between mental representation and the physical world in which functional properties of the physical world are recreated within mental representation. Much as visual imagery may reflect a second-order isomorphism between properties of physical objects and properties of the visual images of those objects (Shepard, 1975), so too might incorporated invariants reflect a second-order isomorphism between properties of physical principles and properties of mental representation. This second-order isomorphism emphasizes phenomenological consequences of physical principles (e.g., "heaviness" rather than "mass") rather than the strict operation of physical principles per se.

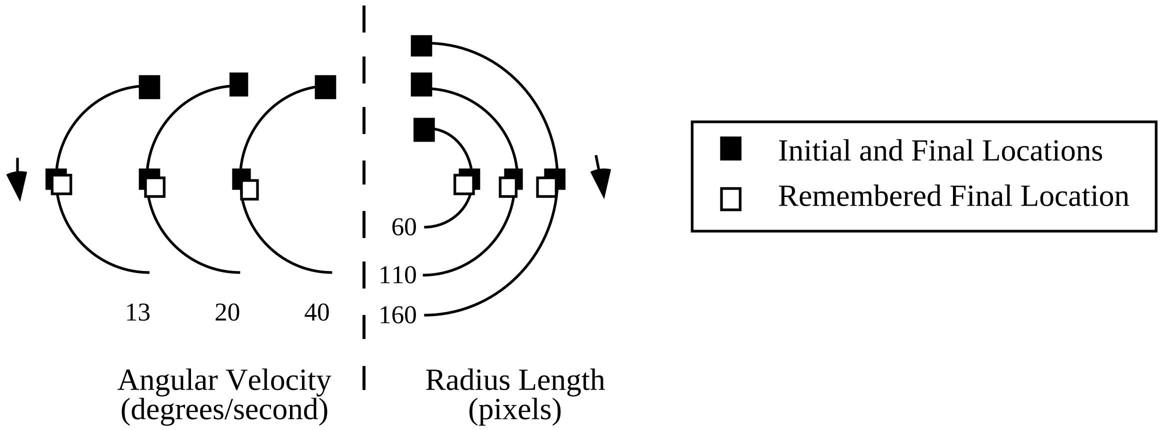

Figure 3. The left panel illustrates effects of angular velocity on representational momentum and representational centripetal force for targets orbiting in a counterclockwise direction. The right panel illustrates effects of radius length on representational momentum and representational centripetal force for targets orbiting in a clockwise direction. Targets move smoothly from initial to final location, and then vanish (without warning) at the final location. After targets vanish, subjects indicate the remembered final position. Representational momentum is shown by the forward displacement along the tangent, and representational centripetal force is shown by inward displacement. Arrows and arcs indicate the direction and path of motion. Adapted from Hubbard (1998a).

The environmental invariants hypothesis goes beyond previous theories that discussed roles of environmental invariants in perceptual or cognitive processing. For example, the environmental invariants hypothesis goes beyond Gibson (1966, 1979) in proposing that mental representations have been shaped by environmentally invariant physical principles, beyond Shepard (1984, 1994) in proposing that information regarding forces and dynamics (as well as information regarding geometry and kinematics) is incorporated into mental representations, and beyond Freyd (1987, 1993) in broadening the reach of spatiotemporal coherence to include all physical principles invariant across human experience. Also, the environmental invariants hypothesis permits effects of invariant physical principles to combine with other information (e.g., observer's expectations, memory averaging; see Hubbard, 1995b) to produce the ultimate displacement of a target.

Applications, Implications and Consequences

Extrapolation of the effects of invariant physical principles is an intrinsic and necessary aspect of mental representation (cf. Finke & Freyd, 1989), and so displacement has the potential to influence a wide variety of cognitive and perceptual processes. A small sampling is reviewed here:

- Findings in “naïve physics” using the “spiral tube paradigm” (e.g., McCloskey, 1983) may reflect a constant representational momentum and a gradually weakening representational centripetal force rather than a “curvilinear impetus” (Hubbard, 1996b).
- Ongoing studies in our laboratory using a version of Michotte's (1963) “launching effect” paradigm suggest that representational momentum for a “launcher” inhibits representational momentum of a launched “target.” This result challenges theories of perceived causality.
- Ongoing studies in our laboratory suggest displacement is influenced by the height of the target in the picture plane in ways consistent with the use of height as a depth cue and with size-distance invariance scaling.
- Representational momentum interacts with the context such that the forward displacement of a target is increased when the target approaches a landmark (Hubbard & Ruppel, in press).

- Boundary extension (i.e., remembering a picture as containing information that might have been present just beyond the boundaries of that picture; e.g., see Intraub, Gottesman, & Bills, 1998) and representational momentum may be examples of a more general mechanism that displaces memory in ways consistent with past experience (Hubbard, 1995b, 1996a).
- Greater success in imaging in a "natural direction" (e.g., Schwartz & Black, 1999) and positive correlations between the magnitude of representational momentum and the speed of mental rotation (Munger, Solberg, & Horrocks, in press) suggest imagery exhibits or includes elements of spatiotemporal coherence.
- Displacement may create mismatches between remembered and perceptually sampled elements, and these mismatches could create violations of expectancies that lead to pleasurable or arousing aesthetic experience (Freyd, 1992).
- Organisms that could anticipate effects of physical principles on stimuli (e.g., prey or predator) would presumably have a survival advantage, and so representational systems may have been "shaped" to automatically extrapolate effects of environmentally invariant physical principles. Thus, displacements should also be found in a variety of nonhuman animals.
- Displacement insures mental representation does not portray the world-as-it-is-right-now, but rather portrays an extrapolated world-as-it-soon-will-be. Displacement may bridge the gap between stimulus and response and thus be a representational equivalent of the reflex arc.

References

Bertamini, M. (1993). Memory for position and dynamic representations. *Memory & Cognition*, *21*, 449-457.

Finke, R. A., & Freyd, J. J. (1989). Mental extrapolation and cognitive penetrability: Reply to Ranney and proposals for evaluative criteria. *Journal of Experimental Psychology: General*, *118*, 403-408.

Freyd, J. J. (1987). Dynamic mental representations. *Psychological Review, 94*, 427-438.

Freyd, J. J. (1992). Dynamic representations guiding adaptive behavior. In F. Macar, V. Pouthas, & W. J. Friedman (Eds.). *Time, action, and cognition: Towards bridging the gap*. Dordrecht: Kluver Academic Publishers (pp. 309-323).

Freyd, J. J. (1993). Five hunches about perceptual processes and dynamic representations. In D. Meyer & S. Kornblum (Eds.), *Attention and performance XIV: Synergies in experimental psychology, artificial intelligence, and cognitive neuroscience*. Cambridge, MA: MIT Press.

Freyd, J. J., & Finke, R. A. (1984). Representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 10*, 126-132.

Freyd, J. J., & Jones, K. T. (1994). Representational momentum for a spiral path. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*, 968-976.

Gibson, J. J. (1966). *The senses considered as perceptual systems*. New York: Houghton Mifflin.

Gibson, J. J. (1979). *The ecological approach to visual perception*. Boston: Houghton Mifflin.

Hubbard, T. L. (1995a). Cognitive representation of motion: Evidence for representational friction and gravity analogues. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 21*, 241-254.

Hubbard, T. L. (1995b). Environmental invariants in the representation of motion: Implied dynamics and representational momentum, gravity, friction, and centripetal force. *Psychonomic Bulletin & Review, 2*, 322-338.

Hubbard, T. L. (1996a). Displacement in depth: Representational momentum and boundary extension. *Psychological Research/Psychologische Forschung*, 59, 33-47.

Hubbard, T. L. (1996b). Representational momentum, centripetal force, and curvilinear impetus. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *22*, 1049-1060.

Hubbard, T. L. (1997). Target size and displacement along the axis of implied gravitational attraction: Effects of implied weight and evidence of representational gravity. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *23*, 1484-1493.

Hubbard, T. L. (1998a). Representational momentum and other displacements in memory as evidence for nonconscious knowledge of physical principles. In S. Hameroff, A. Kaszniak & A. Scott (Eds.), *Towards a science of consciousness II: The second Tucson discussions and debates*. Cambridge, MA: MIT Press.

Hubbard, T. L. (1998b). Some effects of representational friction, target size, and memory averaging on memory for vertically moving targets. *Canadian Journal of Experimental Psychology*, 52, 44-49.

Hubbard, T. L., & Ruppel, S. E. (in press). Representational momentum and the landmark attraction effect. *Canadian Journal of Experimental Psychology*.

Intraub, H., Gottesman, C. V., & Bills, A. J. (1998). Effects of perceiving and imaging scenes on memory for pictures. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 24*, 186-201.

McCloskey, M. (1983). Naive theories of motion. In D. Gentner & A. L. Stevens (Eds.), *Mental models*. Hillsdale, NJ: Erlbaum.

Michotte, A. (1963). *The perception of causality* (trans. T. R. Miles & E. Miles). New York: Basic Books.

Munger, M. P., Solberg, J. L., & Horrocks, K. K. (in press). On the relation between mental rotation and representational momentum. *Journal of Experimental Psychology: Learning, Memory, and Cognition*.

Schwartz, D. L., & Black, T. (1999). Inferences through imagined actions: Knowing by simulated doing. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *25*, 116-136.

Shepard, R. N. (1975). Form, formation, and transformation of internal representations. In R. L. Solso (Ed.), *Information processing and cognition: The Loyola Symposium*. Hillsdale, NJ: Erlbaum.

Shepard, R. N. (1984). Ecological constraints on internal representation: Resonant kinematics of perceiving, imaging, thinking, and dreaming. *Psychological Review*, *91*, 417-447.

Shepard, R. N. (1994). Perceptual-cognitive universals as reflections of the world. *Psychonomic Bulletin & Review*, *1*, 2-28.

*The claim that mental representations respond “as if” influenced by physical forces should not be taken as suggestive of dualism. The point is more subtle: The nature of representation is such that factors influencing a given object need not similarly influence a representation of that object or be literally present within a representation of that object (e.g., a videotape representation of a moving physical target would not experience the same momentum as the actual moving target). Thus, findings that mental representations respond as if influenced by the same physical forces that influence the referent physical objects tell us something interesting about mental representation.