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LAST BUT NOT LEAST

## When is motion ‘motion’?

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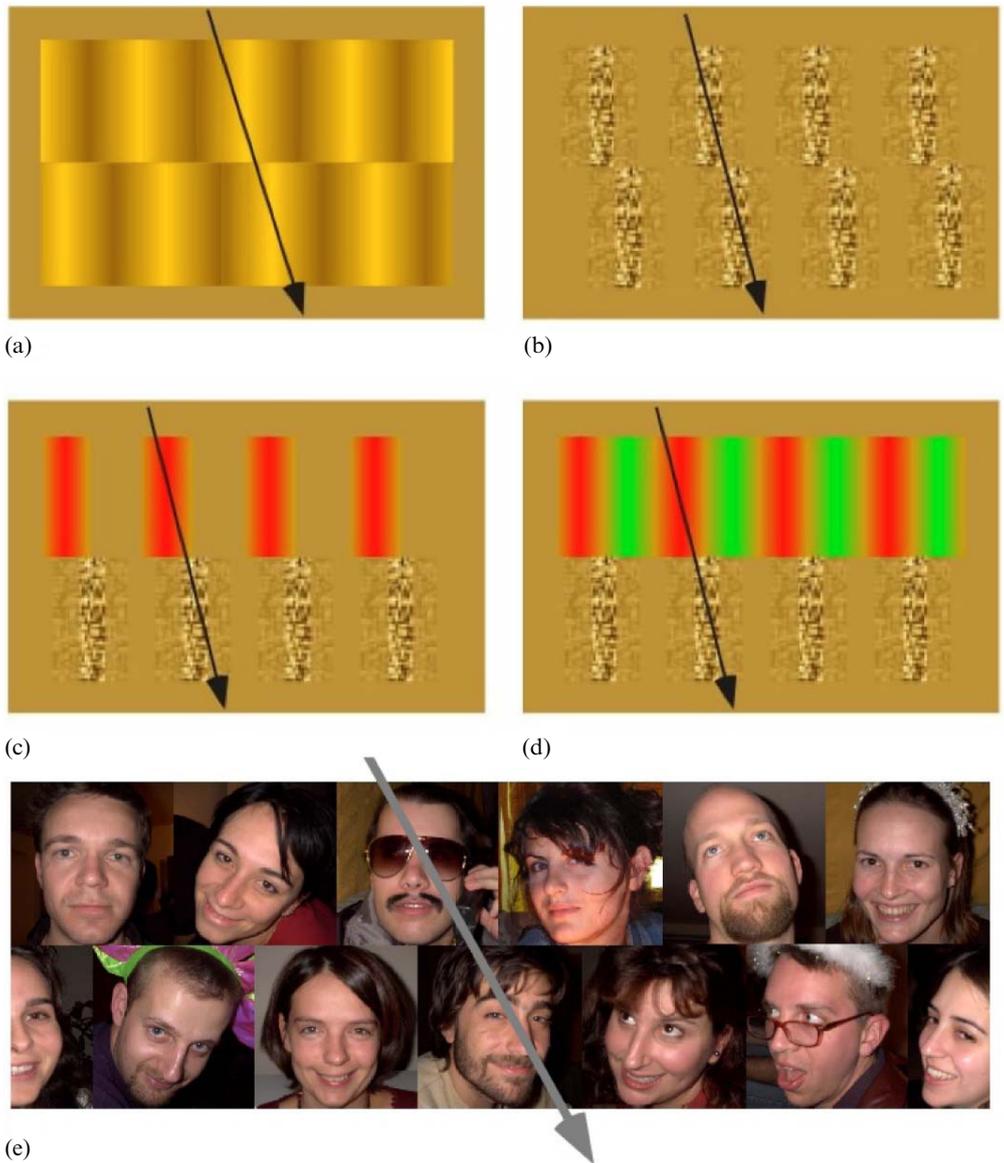
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**Abstract.** Examples of visual motion have become more and more abstract over the years, leading up to ‘third-order’ stimuli where direction is actually determined by the observer through top-down attention. But how far can this be pushed—are there motion stimuli that are yet more arbitrary and abstract? Actually, there is a broad class of ‘conceptual motion’ stimuli—things like a moving grating of faces, or a shifting pattern of words—that are perfect analogs to traditional ‘perceptual motion’ stimuli, solvable by the same motion computation and for which observers can readily make direction-of-motion judgments. Interestingly though, these do not produce a sensation of motion (among other automatic consequences of motion detection). Here we compare a luminance-based perceptual motion stimulus to a semantic-based conceptual motion stimulus to contrast the psychophysical hallmarks of these motion categories.

When is motion ‘motion’? A shifting grating of bright and dark bars is uncontroversially a motion stimulus (figure 1a). So too though are stimuli where displaced regions are not based on luminance, but instead texture, salience, or the observer herself (figures 1b, 1c, and 1d, respectively). How far can such abstraction be pushed? Is a gender-based motion stimulus (figure 1e) really that outlandish, considering recent work showing aftereffects of face-gender (Rhodes et al, 2004)? In all of these cases the pre-processing to determine regions-of-interest—luminance, texture, salience, and gender—is quick, automatic and effortless, and observers can readily make direction-of-motion judgments. And, at an algorithmic level, in all these cases motion can be revealed by the same ‘delay-and-compare’ Reichardt (1961) detector. But, in spite of these commonalities, only some stimuli—‘perceptual motion’ stimuli, as opposed to ‘conceptual motion’ stimuli—evoke a motion sensation and/or other responses such as structure-from-motion, balance and spatial orientation information, smooth pursuit eye movements, motion aftereffects, and collision-avoidance reflexes. We argue that such differences between stimuli that formally are so similar (would a computer vision system treat luminance-based perceptual motion any differently than gender-based conceptual?) reflect the evolutionary priorities of the visual system. Psychophysical comparisons between such stimuli can give insight into these priorities and their behavioral consequences.

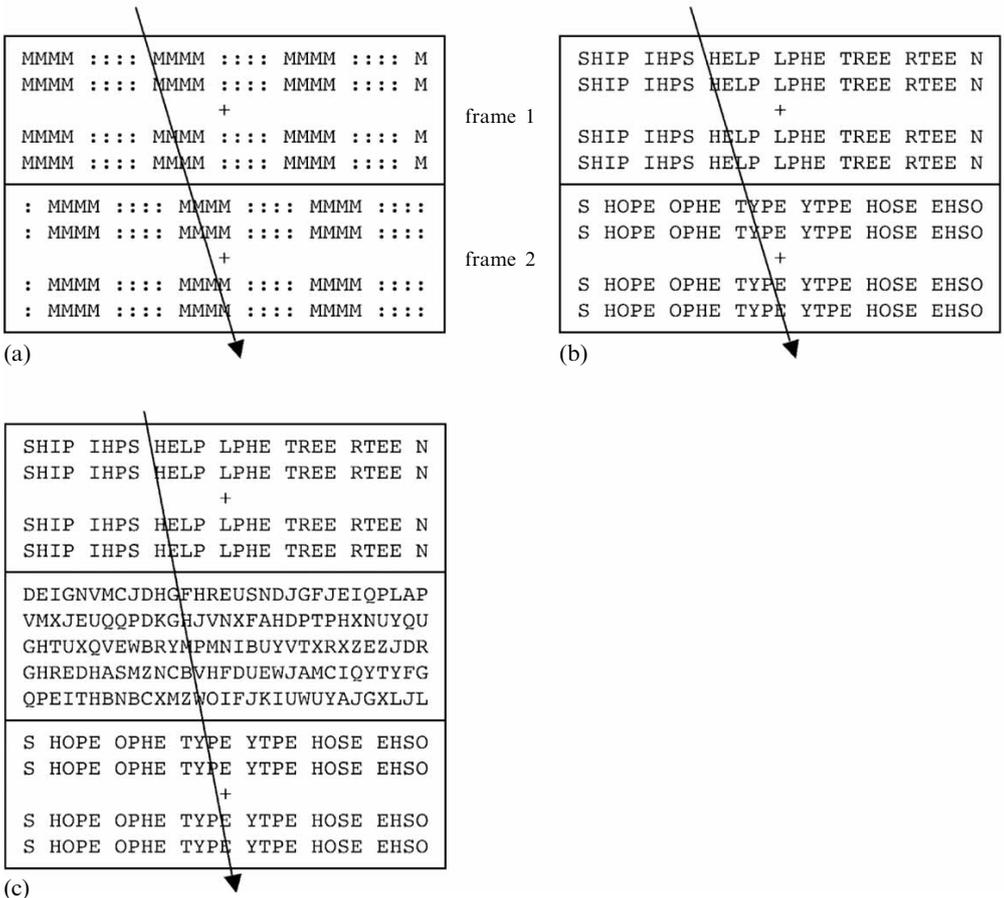
As an exercise in such a comparison, an expert and naive observer were run in a simple experiment that contrasted luminance-based perceptual motion (figure 2a), with semantic-based conceptual motion (figure 2b). One probable psychophysical difference is processing time, as measured by the highest temporal frequency at which observers can discriminate direction of motion at 75% correct. As expected, the cutoff frequency for luminance motion was high, about 7–10 Hz; lower but comparable to the cutoff frequencies found in similar studies of luminance-based stimuli (Lu and Sperling 2001). The cutoff frequency for semantic motion was much lower, about 1–2 Hz. [Interspersed ‘catch’ trials that have no definable direction—composed entirely of word (or non-word) columns for semantic motion or entirely of high-luminance (or low-luminance) columns for luminance-based motion—showed similar cutoff frequencies,



**Figure 1.** [In colour online, see <http://dx.doi.org/10.1068/p5812>] Examples of motion stimuli. Displays consist of a temporal sequence of two spatially coincident frames (ie frame 2 replaces frame 1) containing a grating pattern of some property, yielding: (a) ‘first-order’ luminance-based motion; (b) ‘second-order’ texture-based motion which is statistically isoluminant; (c) ‘third-order’ salience-based motion; (d) ‘third-order’ attention-based motion, where observers are able to break the red–green salience tie by willfully attending to one of the colors [for a review of these motion classes, see Lu and Sperling (2001)]; and (e) a hypothetical gender-based ‘conceptual-motion’ stimulus.

implying observers can also discriminate motion from non-motion, or flicker]. By comparison, exotic attention-based motion stimuli (Lu and Sperling 2001) have cutoff frequencies of about 4 Hz.

Another comparison that is likely to be diagnostic is the effect of visual noise. We introduced a masking field after each motion frame (figure 2c) to distinguish mechanisms based on luminance from higher-level, semantic mechanisms, illuminating which processes



**Figure 2.** Experimental stimuli. (a) The luminance-based perceptual motion and (b) semantic-based conceptual motion display used in our experiments. Columns containing English words alternated with non-words (created by rearranging the characters in word columns, ensuring isoluminance). (c) Example display from the visual masking condition.

limit performance. When a mask follows a frame it determines the effective processing time for any system affected by the mask; processing is cut off when the mask arrives. So, if noise masks are appended to the end of each motion frame, then available processing time is kept constant for mask-susceptible systems like luminance-based ones. But, if performance involves additional processes that are not mask-susceptible—like semantic ones—there is actually more time available for processing (such higher-level processing can continue during the mask exposure). Our results bear this out: performance for luminance-based motion is only marginally reduced by the addition of masks, implying that luminance coding is the primary limiting factor on performance. But semantic-based motion actually *improves* when masks are added. Masks elevate semantic motion performance simply by virtue of providing more semantic processing time, which is evidently the primary limitation on performance. Put another way, adding a mask to the end of each frame decreases effective temporal frequency for conceptual motion, but not perceptual motion. (An interesting speculation is that a ‘semantic mask’—say, a concurrent stream that includes direction words—would selectively target semantic processing, Stroop-like, but leave luminance-motion processing unaffected).

So, when is motion ‘motion’? It seems that while even observer-defined attention-based motion bears a sufficient family resemblance to classic perceptual-motion stimuli like luminance-based motion, semantic-based motion does not. But how strict is this division? While it is trivial to convert perceptual to conceptual motion by pushing spatiotemporal parameters out of bounds (Palmer 1986), could one somehow transform conceptual motion into perceptual motion? [It is tantalizing to consider that semantic motion may already be ‘transformed’ for grapheme-color synaesthetes (Ramachandran and Hubbard 2001)]. There is reason for optimism: Tseng et al (2004) demonstrated that searching for targets of a particular color among distractors of another color increased the salience of the target color, and thereby changed the perceived direction of a previously ambiguous motion display. The enhanced salience, and its effect on motion, persisted for weeks. This suggests that conceptual motion (which way did the red move?) was converted to perceptual motion by making red more salient than the competing color(s).

The pattern of results that we found in our psychophysical comparison was not unexpected. What is interesting are the revealed priorities of the visual system: only those displacements that are likely of immediate relevance to the organism, that is, those that should be detected in a fraction of a second without conscious effort, evolved to have access to special-purpose motion mechanisms of the visual system, which direct their output to, among other targets, a mechanism that yields a conscious sensation of motion. Conceptual motion—slow and effortful—would seem to be distinctly second-class. Its compensatory advantage, though, is its generality. The conceptual motion system has little restriction on the visual tokens that may be displaced [indeed, they need not even be constrained to  $x$ ,  $y$ ,  $z$  space, but could move in a ‘feature-space’ dynamically changing appearance while remaining spatially fixed (Blaser et al 2000)]. With conceptual motion, motion direction is revealed when observers willfully perform a cognitive simulation of the hard-wired Reichardt computation triggered by perceptual motion. The output of the simulation is less visceral—but still useful—it is simply the knowledge of how the stimulus has moved.

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