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## The trade-off between speed and complexity

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**Abstract:** The hypothesis that there has been selection pressure for mechanisms which enable us to perceive the present tends to be conflated with the hypothesis that there has been selection pressure for mechanisms that compensate for inevitable neural delay. The relationship between the two is more subtle, because increases in neural delay can be advantageous for building more useful perceptions.

Proponents of the hypothesis that the brain has mechanisms for perceiving the present (i.e., mechanisms designed to generate a perception at time *t* that is representative of the scene at time *t*) typically say that the advantage is that it helps overcome inevitable neural delays. That is, "latency compensation" and "perceiving the present" have gone hand in hand. I, too, have made this equation in my own articles on how these ideas may be integral to a unified account of illusions (Changizi 2001; Changizi & Widders 2002; Changizi et al., in press; although see Changizi 2003, pp. 75–77). The implicit assumption can often seem to be that natural selection has attempted to minimize neural delays – by shortening wires, speeding up signal propagation, and using rapid computational algorithms for generating a visual percept – and whatever latency between retina and perception is left is handed over to the compensation mechanisms to deal with. Although this is an open possibility, the hypothesis that we perceive the present is not committed to this possibility; it is only committed to the idea that perceptions belong to the present. What is left open is how long the delay is, and whether it is all "inevitable" or whether the delay may be much longer than it would be if selection for short processing times trumped all other selection pressures.

Consider computer software as an analogy. Computer processing speed has risen by many orders of magnitude over the course of the last 20 years, but you may have noticed that many of your programs still take considerable time to start up. Computer designers know how long a wait we are willing to endure, and use that time to carry out fancier computations. That is, when faster computers arrive, computer designers do not appear to be saying, "Now we can compute the same old things nearly instantaneously!" Instead, they seem to be saying, "Now think about how much more we can compute while the user waits!"

Just as computer software delay is a consequence of a trade-off between shorter delay and more complex computations, our perceptual delay is a trade-off between shorter delay and fancier visual computations. For example, if evolution can find a new clever trick for extrapolating farther out into the future – say from 30 msec to 120 msec – then it could utilize this trick and allow itself four times the amount of computation time to build sophisticated useful perceptions. The resultant latency of 120 msec would not be understood as an inevitable delay left over after trying to reduce it as much as possible. Instead, it would be better to say that there is selection pressure to maximize the delay for which the nervous system is able to compensate, thereby buying more time to prepare the perception. Counterintuitively, then, it may well be that the slower-to-react brains are the "smarter" ones.

## Visual prediction as indicated by perceptual adaptation to temporal delays and discrete stimulation

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**Abstract:** Analogous to prism adaptation, sensorimotor compensation for existing neural delays has been clearly demonstrated. This system can also adapt to new delays, both internal and external. This seems to occur at least partially in the sensor systems, and works for discrete, stationary events. This provides additional evidence for visual prediction, but not in a manner that is consistent with spatial extrapolation.

Nijhawan makes a compelling case that the compensation for neural delays must occur at some level, and possibly many levels, of the human central nervous system. In the several sections of this argument, he mentions research from prism adaptation. Prism adaptation is clear evidence that the human central nervous system compensates for its own internal spatial characteristics. If the sensorimotor system can compensate for internal spatial characteristics, might it also be able to compensate for internal temporal characteristics (i.e., neural delays)? As Nijhawan points out, it must, since failure to do so would yield an organism that cannot interact well with the world.

The field of prism adaptation starts with the observation that intersensory spatial arrangements are not constant over the course an organism's life, but change both slowly (e.g., during maturation) and rapidly (e.g., when reaching through water). Any organism that cannot adapt its compensatory mechanisms to deal with changes in intersensory relationships will have nearly as much difficulty interacting with the world as an organism that has no compensatory mechanisms. Prism adaptation shows that human sensorimotor systems can adjust to both rapid and slow changes in intersensory relationships (for reviews, see Bedford 1993; Welch 1978).

Neural delays also change both rapidly and slowly during each organism's lifetime (see, e.g., Ahissar & Ahissar 1994). Thus, if humans can compensate for the temporal characteristics of the sensory systems like they do for the spatial characteristics, might not this mechanism also be able flexible enough to respond to changes in neural delay? Since the 1950s, several researchers have shown that this does not seem to be the case (see, e.g., Sheridan & Ferrel 1963; Smith et al. 1962; 1963). It has, however, since been conclusively demonstrated that not only do humans compensate for external temporal shifts, but the mechanism for doing so is remarkably similar to that involved in prism adaptation (Cunningham et al. 2001a; 2001b). In general, the introduction of an external visual delay initially impairs performance, but a small amount of practice returns behavior to nearly normal levels, and the adapted state generalizes to similar situations. Subsequent removal of the delay produces a large renewed drop in performance as the newly adopted state of temporal compensation ceases to be appropriate (this negative aftereffect is the hallmark of the semipermanent nature of sensorimotor adaptation). Subsequent work has confirmed this effect (Fajen 2007; Fujisaki et al. 2004; Miall & Jackson 2006; Navarra et al. 2007; Stetson et al. 2006; Vatakis et al. 2004; 2007). It is critical here to note that, unlike the visual prediction effect speculated to exist for moving objects, the temporal adaptation effect cannot be completely explained by spatial extrapolation for many reasons, including the fact that it occurs for discrete, stationary stimuli.

Nijhawan focuses explicitly on compensating for continuous events, with special emphasis on moving objects. There must, however, be some form of temporal compensation that also