

It's About Time

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We have all experienced the magic of language, read a passage that was timeless. Language processing, however, is neither magical nor timeless. It is the product of physical processes that unfold in four dimensions, one of which is time. It is therefore striking that time plays so little a role in most current information processing (IP) or connectionist frameworks of language processing.

It is not that IP models ignore time. The assumption that there exists a series of processing stages unfolding over time underlies much IP research and has led to the extensive use of reaction time measures in psycholinguistics. Questions about the number of stages, their durations, and their relative order are staples of IP psycholinguists. Yet in IP models the nature of any particular processing stage is distinct from considerations about its timing; changing the speed of a process or when it occurs does not alter the computation itself.

In feedforward connectionist models as well, time is irrelevant once a network is trained. While hidden layer activations and outputs can be sampled to provide a picture of how and how quickly the network learns a particular task, time does not influence the flow of activity through the network. Time plays more of a role in simple recurrent and constraint satisfaction

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networks where one can ask, e.g., how many time steps it takes for activations to settle or cross a threshold. But, even in these models the nature of processing is generally independent of its timing.

Time and timing, by contrast, are inherent in the neural processes that subservise language functions. Since functional and implementational theories of language must coexist, we suggest that it's about time that psycholinguists take what is known about the brain, and neural timing, seriously, at both methodological and theoretical levels.

Consider, for example, how long retinal processing of a visual stimulus can take: ~ 30 ms for rod-based (low contrast, peripheral) processing and ~ 50 ms for the cone-based (high-contrast, foveal) processing crucial for reading (e.g., Schmolesky et al., 1998). Neural transmission proceeds more quickly thereafter, but it takes ~ 80 ms for the brain to distinguish objects from letter strings and a further 100 ms to appreciate the difference between real and pseudo-words (Schendan, Ganis, & Kutas, 1998). Physical processes take time, and what is known about this timing can help constrain language processing models. Therefore, it's about time that we view time as more than just an independent variable to manipulate or a dependent variable to measure.

The brain receives unlabelled energies from the world and samples these independently and in parallel, via different modalities, different types of receptors within a modality, and different pathways associated with any type of receptor (c.f., DeYoe & Van Essen, 1988). To the brain, a single language stimulus is a set of stimuli, analyzed along different pathways with differing speeds. Early temporal differences, such as that between rods and cones, often become accentuated with further processing, such that areas sensitive to motion (MT) may finish processing before areas sensitive to color (V4) are even aware that there was a stimulus. At the very least, this has methodological consequences: for example, if the characteristics of two stimuli presented in rapid succession are such that the second reaches higher order brain areas first, a backward masking manipulation in the world could inadvertently become forward masking in the brain! Thus, it's about time that we revise our notions of *the* time course of sensory or language processing.

This massive parallelism is not simple redundancy; output from even one type of receptor may impact an area more than once, at different times, and with differing degrees of preprocessing. The processing of even a simple sensory stimulus is not a temporally delimited brain "event." Processing within any given area is distributed over time: from, for example, 40–120 ms in V1, 90–190 ms in inferotemporal cortex, 60–200 ms in prefrontal cortex (Nowak & Bullier, 1997). Intracranial recordings similarly show multiple "waves" of activity in frontal, temporal, and occipital cortex 200–600 ms after a word (e.g., Halgren et al., 1994). Time can serve as a cue about which stimulus features go together (e.g., proposed role of oscillatory activity in feature binding), or as a functional barrier to integration. Neural processing is distributed in time, as well as space, so it's about time to give up the search for the *moment* of lexical access.

At any given moment, then, the brain contains multiple dynamic maps of the environment and the body's surface. These maps vary across individuals and within an individual across time. Even in adults, brain activity and anatomy change with experience, at multiple time scales. Fast electrochemical processes underlying neural communication are influenced by neuromodulatory effects with slower onsets (seconds) that can last from minutes to days. Neuromodulatory systems affect the size—and the timing—of neuronal responses, determining which neurons will fire, how quickly, and for how long (e.g., Tang, Bartels, & Sejnowski, 1997). In turn, electrical and chemical changes lead to structural changes: over hours and years, axons and dendrites branch, synapses are added and removed. So, it's about time that we appreciate that multiple temporal scales are important for examining linguistic events (e.g., words, sentences) that differ in their timing and that multiple measures (especially those with exquisite temporal resolution) are needed.

Brain structure and process thus both depend on time in a way that makes their effects almost impossible to separate. Neural processing is probabilistic, analog rather than digital. It is comparative rather than absolute, relying heavily on context, and reconstructive rather than strictly bottom up, relying on memory retrieval. Such processing is constantly changing and being changed; there are no temporally independent representations. It's about time to give up on the notion of context-invariant word meanings. Time, timing, and the nature of processing are inherently related in the brain. It's thus about time to consider that timing may influence which or how language functions are carried out, not just how quickly or slowly.

In sum, perhaps it's about time that we acknowledge our need for theories of language processing that take time more seriously, for models of language that have a temporal dimension woven into their very fabric, and for better integration between the questions we ask about language and our understanding of the complicated and intrinsic nature of timing in the brain that allowed the human race to develop language, with which to pass along our thoughts about time.

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