Temporal Feature Placing and The Perceived Unity of Time

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While we perceive the temporal structure of events in our environment through multiple sensory systems, we nevertheless perceive all of these events as occurring within a *single unified temporal order* that seamlessly encompasses temporal properties that range from several milliseconds through much longer timescales. The music you listen to, the sound of the voice in the distance, the sight of cars as they pass by, and the vibration of the fan on the table are all perceived as occurring within a single seamless timeline. It is in this way that there is *a unity to time as we perceive it*.

I will argue that the dominant scientific and philosophical approaches to explaining *the perceived unity of time* (PUT) fail. The standard approaches see the explanation of PUT as emerging from a general account of how perceptual processes come to represent the temporal properties of events. However, I will argue that the explanation of how perceptual processes represent temporal properties comes apart from an explanation of PUT. Instead, to explain PUT we need an account of how events, and their temporal properties, are *located at specific moments in time*. Finally, I will argue that this reconceiving of PUT has consequences for the more general literature on the unity of consciousness. In particular, it shows the notions of co-consciousness and the binding problem are much more similar than many have suggested.

Section 1 describes the two dominant approaches for explaining PUT. Section 2 argues that neither of these approaches can succeed since they mistakenly assume that temporal perception is a single homogenous psychological phenomenon. Temporal perception, I argue, is not a single psychological phenomenon, but is instead composed of a number of dissociable capacities to perceive specific aspects of the temporal structure of our world. As a result, no account of PUT can emerge from a general story of how perception represents time since there is no general account of how perception represents time. In section 3, I articulate how to account for PUT we need a representationalist framework within which events and their temporal properties can be located in time. I also argue that in important ways, explaining PUT parallels the task of explaining feature binding in vision. Finally, in section 4, I show the consequences of the conclusion in section 3 for the more general literature on the unity of consciousness.

1. The Standard Approaches

Temporal perception is often treated as though it were a single perceptual capacity.[1] As a result of treating temporal perception as a single perceptual capacity, it is often inferred that there will be *a single account* of how perceptual processes represent the temporal properties of events and that this singular account will provide us with an account of PUT. It is against this backdrop that the two dominant approaches to explaining PUT emerge.

Approach #1: The Supramodal Clock

Internal clock models provide the most widespread framework for understanding temporal perception.[2] According to these models, the temporal contents of perception are the product of a supramodal internal clock that monitors the activity in the individual sensory areas. By monitoring the temporal properties of the activity in sensory areas, the internal clock provides representations of temporal properties that are bound to the individual events perceived by the distinct sensory systems. For instance, an event detected by the auditory system and another by the visual system will be represented as having the same duration if the auditory and visual processes are measured as having the same duration by the internal clock.

In this way, not only does this supramodal clock provide an explanation *for how perception represents the temporal properties of events*, but insofar as the mechanism provides a common cross-modal code for time, it is also supposed to explain PUT. The perception of a single timeline of events is simply the result that all of the events that we perceive, and their temporal properties, are given in relation to this single clock. The unity of the underlying mechanism provides the unity of time that we perceive.[3]

Approach #2: The Mirroring Approaches

According to the other main approach, PUT emerges from an account of temporal representation in which the temporal contents of perception are inherited from (or mirror) the temporal properties of

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[1] In fact, it is often observations about PUT that motivate this view. As it was recently put in a paper by the neuroscientists Hartcher-O'Brien and colleagues (2016), the fact that in perception and in the world temporal properties are all closely related to one another gives us reasons for supposing that there will be a single mechanism for the perception of time.

[2] The internal clock can take on different forms depending on the particular version of the theory. The classic model of the internal clock, as found in *scalar expectancy theory* (Gibbon 1977; Gibbon, Church, and Meck 1984; Zakay and Block 1997) describes the clock mechanism as a simple pacemaker-accumulator system (M. Treisman 1963). The other common form that the internal clock takes, as in the case of the striatal beat theory (Matell and Meck 2004), is of a bank of neural oscillators working in tandem.

[3] In fact, that this is the standard move in the empirical literature is evidenced by the fact that almost all of the empirical work on the multisensory perception of time is given within the framework of internal clock models and how the individual sensory processes relate to this internal clock. See for instance (Wearden 1999).

perceptual processes themselves.[4] To explain the position, it's helpful to introduce an example and some terminology.

Consider a case in which you perceive *a flash of lightning* (L) as standing in some temporal relation to *a crash of thunder* (T). In addition to L and T as represented by perception, we can also talk about *the act* of *perceiving L* (Perc^{L}) and *the act of perceiving T* (Perc^{T}). Perc^{T} and Perc^{L}, as events themselves, have their own temporal properties (e.g. durations, locations in time, temporal relations to other events). As a result, Perc^{L} and Perc^{T} will stand in a particular temporal relation to one another. According to mirroring theories, the perceived temporal relation between L and T will mirror the temporal relation that holds between Perc^{T} and Perc^{L}. Therefore, if Perc^{T} and Perc^{L} are simultaneous, then T and L will be experienced as simultaneous. If Perc^{T} occurs after (or before) Perc^{L}, then T will be perceived as being after (or before) L by the same temporal interval that holds between Perc^{L} and Perc^{T}. According to mirroring theories, this inheritance generalizes to all the temporal contents of perception.[5]

Not only is mirroring supposed to explain how perception represents temporal properties, but if true, it would also provide an explanation for the PUT. Since all of our perceptual processes across modalities occur within a single timeline of events – the timeline in which the subject physically inhabits – then, all of the temporal relations between the events detected across the modalities will hold in the very same way that the temporal relations held between Perc^{L} and Perc^{T}. Therefore, all of the events detected by those processes will be represented as occurring within a single temporal order.

Both of these accounts of the PUT appeal to general theories of how perception represents the temporal properties of events as a means of accounting for the PUT. However, as we'll see in the next section, these two explanatory tasks, explaining how perception represents the temporal properties of events, and explaining the PUT, should be kept separate.

2. The Fragmentary Model of Temporal Perception

As described above, the two standard approaches to explaining PUT treat temporal perception as a single homogenous psychological phenomenon according to which there will be a single account of how perception represents time. It is this treatment of temporal perception that makes their explanations

[4] Examples of this view can be found in (Phillips 2010, 2014; Rashbrook 2013).

[5] Importantly for the mirroring theorist not all of the temporal properties of perceptual processes are inherited as the temporal contents of perception. However, discussing the difficulties that the theory has in delineating which temporal properties of perception can be mirrored in the content of the perceptual process is not something that needs to be done in this paper, as the focus is on how the mirroring theorist approaches explaining PUT.

of PUT remotely plausible. However, as I will argue in this section, temporal perception is not the homogenous psychological phenomenon that they assume it is. Instead, temporal perception is a fragmented phenomenon composed of dissociable capacities to perceive specific types of temporal properties.

The main evidence in favor of the fragmentary model of temporal perception comes from various dissociations between timekeeping capacities. For instance, Rammsayer (1999) showed that haloperidol, a dopamine receptor antagonist, and midazolam, a benzodiazepine, both impair the discrimination of temporal properties of approximately one second in length, but only haloperidol impairs the discrimination of temporal properties of approximately 50ms. Similar dissociations have been found through the application of rTMS to specific brain regions. Koch et al. (2007) showed that application of rTMS to the cerebellum selectively impaired timing in the millisecond range, while Jones et al. (2004) showed that application of rTMS to the dorsal frontal cortex selectively impaired timing in the range of several seconds.

Further evidence shows that timing capacities can be modality specific and specific to particular types of temporal properties. Burr et al. (2007) showed that that the durations of stimuli presented at the target locations of saccades are significantly contracted.[6] Yet this contraction in perceived duration is restricted to visual stimuli located at that specific region of the visual field during saccade. Auditory stimuli, for instance, or visual stimuli presented to other regions of the visual field, were not affected by the saccade. Similarly selective effects have been found in the *oddball illusion* (Tse et al. 2004). In this illusion, people are shown a sequence of "normal" stimuli that are all identical in duration and of the same perceptual type (e.g. same color, same pitch, same shape, etc). Within this sequence of normal stimuli, an "oddball" stimulus is presented which is of the same duration as the normal stimuli but of a different perceptual type (e.g. different color, different pitch, etc). People reliably perceive the oddball as having a duration of up to 50% more than the normal stimuli. Importantly, this alteration in perceived duration has no effect on other temporal properties like flicker rate or motion (Eagleman 2008).

These dissociations show that temporal perception is not a single unified psychological phenomenon, but instead is composed of a number of distinct timekeeping mechanisms that are specialized for particular temporal properties and timescales. However, it's when we look at the emerging models of these specific mechanisms that we find that they often exploit radically different mechanistic strategies in order to represent time. To see this, let's consider two cases from the neuroscience of

[6] Under certain circumstances they were also able to elicit "flipping" in the perceived temporal order of visual stimuli.

temporal perception – the unimodal perception of duration at timescales between 30-350ms, and the crossmodal perception of temporal order at timescales between 250-1000ms.

The unimodal perception of short durations: While internal clock models have dominated the literature for years, emerging theories do away with positing any dedicated clock mechanism. Instead, many theories explain the perception of time by appealing to the intrinsic properties of neural systems. Amongst these types of theories, the *state-dependent network models*[7], have had a significant amount of success in accounting for the empirical data concerning the unimodal perception of duration at timescales between 30-350ms. The model explains the perception of time as being a result of the neurodynamics of localized neural networks that process non-temporal features of stimuli. When a network begins to respond to a particular stimulus, there will be a complex distribution of activity within that network that shifts as a function of time. As a result, the particular subset of active neurons in a localized network can represent the duration of the stimulation (as well as the state of the network immediately prior to the most recent activation).[8] Importantly, if we were to take a snapshot of the brain at a given moment, there would be no single interval of time that these state-dependent network mechanisms represent. Instead, each token mechanism would be representing a particular duration that is attached to the stimulus it is processing.

The multimodal perception of temporal order: While state-dependent network models show promise in accounting for the unimodal perception of short durations, they are not up to the task of accounting for the multimodal perception of temporal order. Instead, the dominant models of multimodal temporal order perception involve an opponency mechanism (Cai, Stetson, and Eagleman 2012; Stetson et al. 2006). The model developed by Cai et al (2012) involves a number of delay-specific neurons that fire for specific temporal discrepancies between processing in sensory areas. These delay-specific neurons then send excitatory and inhibitory signals to a pair of summation cells. These summation cells constitute a pair of *earlier than* and *later than* neurons, in which the relative activation of these two cells represents the temporal order (and the separating interval between) two events.

[7] Developed by in a series of papers by Dean Buonomano and colleagues (Buonomano 2000; Buonomano and Karmarkar 2002; Buonomano and Maass 2009; Finnerty et al. 2015; Ivry and Schlerf 2008).

[8] Karmarkar and Buonomano (2007) explain the model on the basis of an analogy. Imagine dropping a pebble into a bucket of water. The pebble will cause a complex pattern of ripples to travel across the surface of the water. The particular spatial distribution of ripples at any given moment will be a function of the hydrodynamics of water, the characteristics of the pebble and how it was dropped, the initial state of the water's surface, and the amount of time that had passed since the initial dropping of the pebble. The similar sort of "rippling" in the neural networks is due to a complex assortment of short term plasticity mechanisms. For a description of these details see (Buonomano and Maass 2009).

Perhaps most importantly for the development of these models, they are designed to explain the way in which temporal order perception is sensitive to *on-the-fly recalibration* due to sensory adaptation (Stetson et al. 2006; Vroomen et al. 2004). For instance, in a series of experiments it has been shown that if a delay is inserted between a subject's pressing of a button and the appearance of a flash of light on a screen, subjects will slowly begin to perceive the button press and the flash of light as occurring closer together in time as their perceptual system adapts to the inserted delay. However, when this delay is suddenly reduced (or removed altogether) subjects perceive the two events as occurring much closer in time than they in fact occur. In extreme cases, the actual order of events is perceived as being flipped (i.e. the flash of light comes before pressing the button)!

This recalibration shows that the temporal order represented in perception comes apart from the temporal structure of the perceptual processes themselves. A pair of stimuli, *A* and *B*, might be perceived as *A preceding B* or *B preceding A* because of the perceiver's state of adaptation (even though A and B might be presented identically in both cases and the timing of sensory processes is identical in both cases). Furthermore, these mechanisms only represent the temporal relation that holds between a pair of events. When the mechanism represents A as preceding B by a certain interval, it does not commit to whether A, B, or some point in the interval is *now*. That is, it does not say *when* these events occur, rather it only expresses the relation between these events.

The picture of temporal perception that is emerging is one in which there is no general explanation for how temporal properties are represented in perception, since temporal perception itself is composed of an assortment of distinct types of representational mechanisms. Therefore, no explanation of PUT can emerge from a general account of how temporal properties are represented in perception, since no such general account is possible. The two approaches described above fail.

3. The Perceived Unity of Time

The mechanisms described in the previous section all attribute temporal properties to events. However, what these mechanisms do not do is represent *when* these events are occurring. That is, they do not place the events and temporal properties they represent at any specific location in time. It is this placement that needs to be accomplished in order to explain PUT, since only then will we be able to explain how the events in perception are perceived as inhabiting a single seamless temporal order.

One thing that we can conclude about this type of event placement is that it cannot be explained by exploiting the temporal structure of perceptual processes themselves. The evidence pointed to above, in particular the work on the opponency systems that represent temporal order, shows that the temporal contents of perception come apart from the temporal structure of perception. The localization of events in time cannot be explained the locations in time that the perceptual experiences of those events inhabit.[9]

Instead, any account of PUT must provide an account of a representational framework within which the events perceived by the various sensory systems can be located. In many ways, the event placement needed to explain PUT parallels the feature-placing found in accounts of visual feature integration and the binding problem (Clark 2000, 2004; Treisman and Gelade 1980). In the literature on visual feature integration, theorists are faced with the task of explaining how it is that individual visual features, represented by distinct representational mechanisms, can be perceived as being located within a single unified spatial field, and thereby allowing for the co-location of features in the perception of unified objects (e.g. the co-location of the features redness and roundness in the perception of a tomato as being red and round).

Where the explanation of PUT and the explanation of visual feature integration and the binding problem come apart is that in the integration of visual features, explanations exploit the existence of multiple feature specific retinotopic maps that each individually represent the same visual space. The integration of visual features represented across these visual maps is a process in which the individual maps are put into correspondence with one another. However, in the temporal case, the individual temporal properties represented in perception are not encoded in anything that can be considered a *temporal map*, let alone are all the temporal properties represented in perception represented by temporal maps that represent the same interval of time.

The problem of explaining the PUT and explaining visual feature integration are similar, yet the explanation of the PUT will differ significantly from the explanation given for visual feature integration. In both cases integration must occur through a representational framework in which features / events can be located, but the representational framework in both cases will be structured very differently.

4. From PUT to The Unity of Consciousness

While there are various things that fall under the title of 'unity of consciousness' one particular central interpretation of the term is that of *co-consciousness*. As Tim Bayne puts it:

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[9] This also includes accounts in which an additional clock might be used to monitor these individual timekeeping mechanisms in order to locate these temporal properties in time, since again, the temporal structure of these timekeeping mechanisms would come apart from their content.

> […] a person's simultaneous conscious states are typically contained unified within an overall phenomenal 'perspective' or 'field'. My experiences of hearing the music of Mingus, seeing words on a computer monitor and tasting olives do not occur in isolation from each but occur together, as components of a phenomenal whole. States that are unified in this way are said to be […] 'co-conscious'.
>
> (T. Bayne 2009)

As it is typically taken in the unity of consciousness literature the explanation of co-consciousness is substantially different than "object unity" in which disparate features are attributed to common spatial locations or unitary objects. That is the notion of co-consciousness is taken to be distinct than that of the binding problem since solving the binding problem seems to leave out an explanation of co-consciousness (Bayne and Chalmers 2003; T. Bayne 2009; Brook and Raymont 2014).

Yet, Baynes' characterization of co-consciousness is just a case of PUT. The example of co-consciousness can be re-described as a case in which disparate events are perceived as occurring within a single temporal order – some things happening simultaneously, others not. If the above arguments are correct, and the problem that arises in explaining PUT parallels the problem that arises in the binding problem, then co-consciousness and the binding problem are in fact not distinct types of problems. In this way, a substantially puzzling aspect of the unity of consciousness, co-consciousness, can be replaced by a more empirically tractable and familiar account of explaining PUT.

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