# Experience and the Pacemaker-Accumulator Model*

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Abstract: The pacemaker-accumulator model provides a framework in which the results of different duration estimation tasks are commonly accounted for. Nevertheless, the model remains abstract and it does not provide proper explanations nor predictions for duration estimations in various experimental set-ups. This paper aims to address these shortcomings by explicating the experiential pacemaker-accumulator model that supplements the standard pacemaker-accumulator model with two claims. Both of them concern the role that experiences play in duration estimation tasks and are also partly supported by studies not directly related to duration estimation. First, the internal responses based on which the switch between the pacemaker and the accumulator operates are the same as the neural processes that realize conscious access to experiences. Second, the processes that realize the experiences of stimuli realize the function of the pacemaker. By supplementing the standard pacemaker-accumulator model with these claims, the model affords proper explanations for the systematic errors and empirically testable predictions in duration estimations tasks. One likely consequence of the model is that the experience of duration and the duration of experience can differ.

## 1. Introduction

When presented with two stimuli in succession, we can often determine with some accuracy whether they have the same duration and, if not, which one lasted a shorter time than the other. This ability to make judgements about durations, sometimes called duration estimation and time perception, has been studied experimentally since the early days of psychology. Unsurprisingly, various theories have been put forward to account for it (for recent reviews, see Grondin 2010; Matthews & Meck 2016).

One particularly influential explanatory framework that has emerged is *the pacemaker-accumulator model*. It specifies three functions that are thought to be required for duration estimations. The first one is the *pacemaker,* which generates a stream of pulses in a way similar to a metronome. Secondly, duration estimation requires the counting of the pulses provided by the pacemaker. This function is served by the *accumulator*. Thirdly, there is the *switch* between the pacemaker and the accumulator. Its task is to control the stream of pulses from the pacemaker to the accumulator. When the duration estimation task begins, the switch opens and the pulses generated by the pacemaker reach the accumulator. When the task ends, the switch closes and the accumulation of pulses ends. The duration estimation is based on the total number of pulses that reach the accumulator (Church, 1984; Gibbon, Church and Meck, 1984).

Various non-temporal factors distort our performance in systematic ways during the duration estimation tasks. These factors include both the properties of the stimuli (e.g., size,

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speed, valence, and modality of stimulus) and the properties of the participants (e.g., their age and personality traits, and the allocation of attention). As illustrated in the examples below, the pacemaker-accumulator model explains these distortions in terms of the rate of the pacemaker and the operation of the switch (e.g., Wearden et al. 2007). Although uncommon, sometimes the explanations for the distortions refer to variance in the memory of the presented stimulus (e.g., Penney et al. 2000; Jones & Wearden 2003).

Many scientists consider this standard version of the pacemaker-accumulator model (shortly, PAM) to be only a metaphor. This is possibly (at least partly) because the mechanisms which implement the three functions of the model in the brain remain elusive (especially for the pacemaker) and, subsequently, the model and the explanations it affords us remain abstract. Nevertheless, PAM remains influential as a useful outline of the functions that many think may be involved in the duration estimation tasks, even if neural mechanisms that implement it are not known. Increasingly, many duration estimation studies explain their results in terms of this model.[1]

Despite its popularity, PAM can be justifiably criticized for two (interrelated) theoretical shortcomings. First, PAM, and the ways in which it accounts for the distortions in duration estimation, lacks a description of what grounds the operation of the switch. Demonstrably, researchers do occasionally comment on the features of external stimuli as the markers based on which the duration estimations are performed (e.g., Staddon 2005; Wearden et al. 2014), but the switch cannot operate based on those markers. This is because the switch, which operates between the pacemaker and the accumulator, does not have an access to the stimuli as it is external to the subject. Instead, the switch must operate based on some internal response to the stimuli or changes in stimuli. Likewise, the suggestion that attention influences the operation of the switch commonly describes how attention is directed to the external stimuli, making the effect of attention to the switch indirect. In short, PAM lacks a description of the internal response and hence does not describe all the necessary elements required for duration estimation.[2]

The second shortcoming is well summarized by Matthews and Meck (2016, p.11): "[A] major limitation of the pacemaker framework is that [it] makes no predictions (and offers no explanation) regarding *which* dimensions [of stimuli and participants] will affect subjective duration, or of the direction of these effects." Indeed, some of the model's explanations for duration estimations are unsatisfactory at best and, at worst, outright incorrect (or so I will argue).

The objective of this paper is to amend the first shortcoming, which subsequently addresses the second shortcoming as well, at least partly. This is done by explicating and elaborating on the implications of a view I call *the experiential pacemaker-accumulator model* (EPAM). This view maintains that our experiences of stimuli play two roles in the duration estimation tasks. First, the internal responses on the basis of which the switch operates are the

[1] For this reason, the following discussion will make use of the pacemaker-accumulator model rather than less commonly held alternatives such as theories based on state-dependent network (Karmarkar & Buonomano 2007) or striatal beat frequency model (Buhusi & Meck 2005; Meck et al. 2008).
[2] This does not mean that researchers have ignored the internal response to the stimuli altogether—a claim that is patently incorrect (see sections three and four). Quite the contrary, the purpose is only to point out that it is not included in PAM.

same as the neural processes that realize conscious access to the experiences of the stimuli. Second, the processes that realize the experiences can realize the function of the pacemaker. Whereas the former claim can often be thought to be implicitly assumed in the duration estimation studies, a version of the latter claim has previously been explicitly maintained. However, the full implications of these two claims have not been explicated.

In what follows, section two details the first claim, namely that the switch operates based on conscious access to experiences, and explicates the assumptions underlying the claim. Section three elaborates upon and defends the claim that experiences constitute the pacemaker. The resulting view, EPAM, invites us to revisit PAM's original explanations of the systematic distortions in duration estimation. This task is undertaken in sections four and five. They describe how EPAM can account for two major duration distortions for which a truly explanatory account in terms of PAM has remained elusive: the modality effect and the filled-duration illusion. These examples highlight how EPAM is empirically more tractable than PAM and affords us with a better and more parsimonious explanation of duration estimation, thus partly addressing Matthews and Meck's objection. Finally, section six concerns the possibility of having experiences of duration (phenomenological experiences of duration) in the provided framework.

## 2. Conscious access to experience as internal response

The first way in which I suggest PAM be supplemented is by adopting the claim that conscious access to the experiences of the stimuli (or their features and changes in features) is the internal response based on which the switch operates. This idea immediately gives rise to a question: what is meant by conscious access to the experiences? For the purpose of this paper, conscious access is understood in the framework of dissociative theories of consciousness, which separates perceptual consciousness from cognitive access (Block 2005; Block 2007).[3] According to this framework, perceptual systems represent the stimuli and bring about the phenomenology of experiences. When the represented information is globally "broadcasted", we have conscious access to it and the information can be utilized by all cognitive mechanisms without further processing. That is, when the state of perceptual consciousness is made available to cognitive processing in this way, it can be used for reports and storage in working memory, for example. In neural terms, it has been suggested that perceptual consciousness requires local reentrant processing (i.e., a feedforward-feedback loop confined within each sensory modality), meaning that the properties represented in the early sensory cortices are also relevant for experiences, whereas global broadcasting involves global reentrant processing incorporating the frontal cortex (Lamme & Roelfsema 2000; Lamme 2006). There are also other suggested claims, but they too separate the processing taking place within the sensory cortices from the processing involving the frontal cortex.

[3] I adopt the framework of dissociative theories of consciousness because it allows the most straightforward way of explaining the two roles I wish to attribute to the experiences in EPAM, not because EPAM necessitates the framework. That is, I take it that EPAM can also be formulated in the frameworks of Global Workspace theory (Baars 2002) and Higher-Order thought Theory of consciousness (Rosenthal 2005; Lau & Rosenthal 2011).

Not only is the suggestion that conscious access to the experiences controls the switch compatible with the pacemaker-accumulator model in general—after all, the model does not comment on the nature of internal response on the basis of which the switch operates—it is also not prima facie implausible. For instance, duration estimation tasks require participants to estimate how long they experience events to last. Hence, the claim that duration estimations are not based on experiences would require additional justification and explanation. But such tasks require reportability, and this in turn requires conscious access to the experiences. Second, the suggestion that conscious access to the experiences controls the switch concurs with findings that most commonly used duration estimation tasks (which involve stimuli lasting half a second or more) involve prefrontal activity and require working memory (Lewis & Miall 2006; Lewis & Miall 2003)—sometimes working memory is even taken to serve the function of the accumulator (see Kanai & Watanabe 2006; Lewis & Miall 2006). Third, conscious access to an experience requires attention. Hence, it follows that, at minimum, the operation of the switch depends in part on attention. It could even be that attention is the switch controlling the estimated duration of a stimulus. Both alternatives concur with suggestions previously made in relation to the pacemaker-accumulator model: that attention influences the operation of the switch.

If the switch operates based on conscious access to the experience, it follows that the duration of the experience plays a critical role in duration estimations; the duration of the experience governs the operations of the switch, and therefore also governs the interval during which the pacemaker's pulses reach the accumulator.[4] The duration of experience does not determine the estimated duration, however, because the duration estimations also depend on the rate of the pacemaker. This leads to two predictions. First, variation in the duration of experience is reflected in variation in the estimated duration. This prediction is supported by the studies mentioned in section four. Second, while the duration of experience and the estimated duration correlate, they are not the same and can deviate from one another. This issue was examined by Bendixen, Grimm, and Schröger (2006) by employing both EEG recordings and psychophysical methods. They report that the response stimulus interval (RSI) modulates estimated durations differently than it modulates the durations of experience, which were determined separately by means of event-related brain potentials as well as reaction times to onset and offset of stimuli. Because onset, offset, and duration estimation tasks all used the same stimuli, this difference in modulation implies that the estimated duration and the duration of experience are not the same.

It is import to note that it is assumed throughout this paper that the temporal properties of the experience of stimuli (a phenomenological state) match the neural processes that realize the experience. This indicates subscription to the *thesis of temporal isomorphism*, according to which the point in time that something is experienced to occur is isomorphic to the time when neural processes realize the experience. For example, if two flashes ($F_1$ and $F_2$) are shown and the experience of $F_1$ is neurally realized before that of $F_2$, then $F_1$ is experienced before $F_2$. And conversely, if $F_1$ is experienced before $F_2$, then the neural states that realize these

[4] Even if the duration of the experienced governs the duration for which the switch is open, it does not follow that the two durations are the same. This is because the operation of the switch is thought to have its own latency. This possibility is ignored in the paper because such a claim is postulated on the basis of certain results and is not needed if EPAM is accepted (see also section four).

two experiences also occur in this order. Understood in the context of duration of experiences, the thesis of temporal isomorphism states that the duration of an experience matches the duration of the neural processes that realize the experience.

The thesis of temporal isomorphism has been most famously challenged by Daniel Dennett and Marcel Kinsbourne (1992). Their challenge was based on explanations for the color phi phenomena, cutaneous rabbit phenomenon, and the backward metacontrast masking. These and related phenomena can, however, also be plausibly explained by subscribing to the thesis of temporal isomorphism. Hence, the status of the thesis in relation to these phenomena remains in dispute (see for example Arstila 2015b; Eagleman & Sejnowski 2000; Grush 2005; Grush 2007; Whitney et al. 2000). Since Dennett and Kinsbourne's influential paper, there has also been a debate concerning the thesis of temporal isomorphism in relation to the topics of cross-modal simultaneity perception (e.g., Nishida & Johnston 2010; Yarrow & Arnold 2015) and the perceived simultaneity of changes occurring in visual stimuli (e.g., Moutoussis & Zeki 1997; Moutoussis & Zeki 2002; Nishida & Johnston 2002; Arstila 2015a).

While the thesis of temporal isomorphism has been under scrutiny with regard to the timing of experiences of two (or more) events—as the three topics above illustrate—it is largely ignored in relation to the duration of experiences, and such a relation remains implicitly assumed in many of the studies cited below. A competing theory has been presented, however, according to which the duration of experience is represented by the non-temporal features (namely strength) of the neural activation realizing the experience rather than the duration of activation (Noguchi & Kakigi 2006). I will return to the thesis of temporal isomorphism and the competing theory at the end of sections three and four.

## 3. Experience as the pacemaker

PAM originally presented the pacemaker as a single universal pacemaker used in all duration estimation tasks. The second claim I suggest supplementing this model with is that the processes that realize the experiences also realize the function of the pacemaker. The two are at least so closely related that, for our intents and purposes, they are the same. If this claim is true, then there is no single pacemaker, not even a modality specific one.

One possibility concerning how the function of the pacemaker could relate to experiences is that the rate of the pacemaker correlates with the (relative) strength of the neural processing concerning the experiences. The stronger the neural activation, the higher the rate of the pacemaker. This idea concurs with findings showing that stimulus intensity influences both the strength of the neural processing (Polich et al. 1996) and the estimated duration of the stimulus (Goldstone et al. 1978; Matthews et al. 2010). If one assumes that the visibility of a stimulus correlates with the (relative) strength of neural activation (as argued by Moutoussis & Zeki 2002), this possibility also provides a parsimonious explanation for why duration estimations correlate with the visibility of the stimuli (Terao et al. 2008): strong neural activation leads to both better visibility and increased pacemaker rates.

It is also possible that the function of the pacemaker is linked to conscious access, meaning that the function of the pacemaker is jointly realized by attention and the neural processing related to the perceptual consciousness. In this case, top-down attention, which is thought to sample information periodically, would bring about the pacemaker's "pulses". Under this proposal, however, pulses are unlikely to consistently have the same impact because the rate of attentional sampling does not change much. Accordingly, the "value" of the pulses would correlate with the strength of the neural processing concerning the experiences. In this situation, the number of pulses would not be the only thing of consequence in duration tasks, and one pulse related to a strong neural activation would have the same influence as two pulses related to a weak neural activation.

In either case, the function of the pacemaker is closely related to the processing of experiences. According to my knowledge, such a claim—or at least a similar one—was first argued for by Johnston, Arnold, and Nishida (2006) based on their results showing that distortions in duration estimations can be confined to localized regions of visual space. In their study, the distortion was caused by an adaptation to flickering stimuli and the distortion of duration estimation was restricted to the visual area in which the flicker was presented. A temporal order judgment task showed no difference between the onsets and offsets of the stimuli when presented onto the adapted and non-adapted area, therefore indicating that the distortion was not due to changes in the onset and offset of experiences. That is, the effect was not due to different durations of the experiences.

Johnston, Arnold, and Nishida's results challenge the idea of a universal pacemaker employed by all sensory modalities (or even one modality; see section five), because if such a pacemaker exists, adaptation to the flickering stimulus should have a global affect rather than a local one. Thus, they (2006, p.477) conclude that "[t]he spatial specificity of the adaptation effect argues against a single universal internal clock" and "that peripheral, spatially localized and essentially visual sensory processes are involved in the encoding of duration." One interpretation of these claims is that "the [pacemaking] pulses come from the units representing the stimulus" (Matthews & Meck 2016, p.25). That is, the neural states that realize the experience of the stimulus can also be the pacemakers.

In addition to Johnston, Arnold, and Nishida's (2006) results, the idea that the neural processing related to experiences plays the role of pacemaker provides a parsimonious explanation for several questions and findings. For example, Yarrow and colleagues (2001) showed that saccadic eye movements distort the estimated duration of a visual stimulus and that the duration of the saccade almost perfectly matches the underestimation of the duration of the stimulus. This effect is restricted to the visual modality since the estimated duration of an auditory stimulus is not affected by saccades (Morrone et al. 2005).

EPAM explains such findings as follows: given that we are unaware of the visual stimuli presented around the time saccades occur, then if the neural processing related to experiences realizes the pacemaker, the saccades block the pacemaker's pulses from reaching the accumulator. Consequently, the duration estimations for visual stimuli presented around the time the saccades occur are shorter than those of visual stimuli presented at other times, and this "lost" time matches the duration of the saccades. Because saccades do not suppress the perception of auditory stimuli, the estimated duration of those stimuli are not affected by saccades.

Second, PAM explains the distortions in duration estimations mainly by postulating changes in the rate of the pacemaker. Attention to a stimulus, for example, increases the rate of the pacemaker and the duration estimations for attended stimuli are therefore longer than those of unattended stimuli of the same objective duration. This does not explain, however, why the rate of the pacemaker correlates with the level of attention. After all, if the representations of stimuli and the pacemaker are different, then why would attention to stimuli influence the pacemaker? Similarly, PAM does not explain why the properties of stimuli (e.g., luminance, valence, speed) influence the rate of the pacemaker; if the representations of the stimuli and the pacemaker are independent, why do factors related to the former also affect the latter?

However, neither of these types of distortions are inexplicable if the function of the pacemaker is realized by the neural correlates of the experience. In fact, in this case it follows by necessity that if attention influences the properties of the neural states that process the properties of the stimuli, attention also influences the rate of the pacemaker. Likewise, given that different properties of stimuli cause different neural activation, it follows that the properties of stimuli influence the rate of the pacemaker.

Before turning to major distortions in duration estimations, let me return to the thesis of temporal isomorphism. One study that appears to challenge this thesis is that of Noguchi and Kakigi (2006), which reports that the estimated durations of experiences correlate better with the strength of "the neural index" (the neural correlate of an experience) than with the duration of the neural index. Accordingly, the authors (2006, p.1797) conclude that "subjective intervals are closely linked to the strength, not timings, of neural activity evoked by visual patterns." However, in light of EPAM, this conclusion appears to exaggerate the significance of the findings because duration estimations depend on both the rate of the pacemaker and the interval during which the pulses generated by the pacemaker reach the accumulator. Accordingly, in some cases, duration estimations are likely to correlate closely with the duration of the experience (the duration of the neural index), and in other cases (assuming roughly the same durations for the used stimuli) it may correlate more closely with the rate of the pacemaker. Occasionally, the effects of the latter can be stronger than the former: a brief experience, for example, could be estimated to last unusually long because of the rate of the pacemaker. Thus, Noguchi and Kakigi's results only illustrate that which is to be expected in the framework of EPAM: that the duration of the experience (or its neural index) does not determine the estimated duration.

Noguchi and Kakigi's (2006) claim is very similar to Pariyadath and Eagleman's (2007) explanation for the oddball effect.[5] Roughly explained, their idea is that subjective duration reflects the size of a neural response (by "subjective duration" they mean the estimated duration of the stimuli). While the processing of the repeated stimulus becomes increasingly suppressed and the neural response decreases, the oddball stimulus, as a new stimulus, engages more neural processing (which could be due to attention) and hence its subjective duration also increases. If the oddball stimulus does cause stronger neural response, then EPAM states that

[5] The oddball effect refers to a robust finding that an unexpected (oddball) stimulus presented in the middle of the train of standard stimuli (all having the same duration) is estimated to last longer than all other stimuli except the first. The relative difference between the estimated durations depends on the location of the oddball stimulus in the train of stimuli—the first stimulus is estimated to have the same duration as the oddball stimulus, and the duration of the second is estimated to be little bit shorter than the first stimulus, the duration of the third stimulus is estimated to be a bit shorter than that of the second , and so on. (Tse et al. 2004)

the oddball should obtain the increased rate of the pacemaker, which subsequently leads to the increased duration estimations. Thus, Pariyadath and Eagleman's explanation for the oddball effect does not challenge the thesis of temporal isomorphism after all, but is wholly compatible with the broader explanatory framework EPAM affords us.

## 4. Modality effects on duration estimations

Modality effects refer to the effects of the modality of stimuli on the duration estimation tasks. The effect is often investigated by presenting continuous light and sound in succession and asking participants to compare their durations. The three most significant findings are that (i) visual stimuli are estimated to last for a shorter time than auditory stimuli of equal objective duration, (ii) the difference between the estimated durations of auditory and visual stimuli increases with the duration of the used stimuli (the so called "slope effect"), and (iii) visual stimuli produce more variable duration estimations than auditory stimuli. (Wearden et al. 2006; Wearden et al. 1998)

PAM explains the first finding by postulating that the rate of the pacemaker is faster for the auditory modality than visual modality. Thus, during the same objective duration, the accumulator counts more pulses for auditory stimuli than it does for visual stimuli and therefore the auditory stimuli are estimated to last longer than the visual stimuli. This explanation also accounts for "the slope effect", which cannot be due to the constant difference between the onset and offset times for auditory and visual stimuli. The third finding, in turn, is explained by postulating that the switch between the pacemaker and the accumulator functions in a more variable manner for visual stimuli than for auditory stimuli. Since the switch controls which pulses from the pacemaker reach the accumulator, the increased variability in the operation of the switch leads to increased variability in duration estimations. (Wearden et al. 2006; Wearden et al. 1998)

Arguably, PAM's explanations for the findings leave much to be desired. After all, even if we accept that auditory and visual modalities have a separate pacemaker, their different rates are postulated, not explained. Likewise, even if we accept the postulation that the switch operates differently for auditory and visual stimuli, the reasons for why this is so are not explained.

The two claims EPAM adds to PAM provide two new explanations for modality effects. First, consider the claim that the pacemaker is realized by the same neural processes that realize the experience of the stimulus. If this holds, then the first finding can be explained by postulating that saccades occur during the experimental tasks. On the one hand, this means that no pulses reach the accumulator during the saccades when estimations are made based on visual stimuli. On the other hand, as discussed above, the saccades do not affect the estimated duration of auditory stimuli. Accordingly, during the same objective duration, the accumulator counts more pulses for auditory stimuli than for visual stimuli, and the visual stimuli appear briefer than the auditory stimuli. This explanation also accounts for the slope effect, because the probability of the saccades occurring increases with the duration of the stimuli used. Thus, whereas there might be no saccades during a brief stimulus, there could be many when the stimulus is longer. Consequently, longer stimulus durations lead to larger differences in the estimated durations of auditory and visual stimuli. In this way, the first two findings can be accounted for without postulating any difference in the rate of the pacemakers.

The third finding was that visual stimuli produce more variable duration estimations than auditory stimuli. Since the number and size of saccades determines how much time is lost during each presentation of a visual stimulus, saccadic suppression can explain this finding as well. For example, if only one small saccade occurs during a presentation of a visual stimulus and then two larger saccades occur when a similar visual stimulus is presented, the difference in the amount of time lost due to the saccades is considerable. Duration estimations for auditory stimuli show less variability because they are not influenced by saccades.

The second explanation for the first and third findings is compatible and cumulative with the previous explanation. It is based on the different durations of the auditory and visual experiences and the different variability thereof. Similarly to the first explanation, this second explanation is also supported by the empirical results. On the one hand, the onset and offset latencies for auditory stimuli in the auditory cortex are the same and show little variation (at least in cats; Qin et al. 2007). Thus, the duration of the internal response to auditory stimuli quite precisely reflects the duration of the stimuli. On the other hand, compared to offset latencies, the onset latency for visual stimuli in the visual cortex is much longer and shows more variability (Bair et al. 2002; Walsh 1973). Since the offset latency mirrors the offset of the stimuli more precisely than the onset latency mirrors the onset of the stimuli, the duration of the experience of visual stimuli is indeed slightly shorter than the visual stimuli and, subsequently, than the experience of auditory stimuli. To put this somewhat differently, PAM's implicit assumption that equal duration of stimuli produces experiences with equal durations is not always justified. Moreover, given the variability in the onset latency of visual stimuli, the duration of the visual experience varies more than the duration of the auditory experience. Consequently, it follows that duration estimations concerning visual stimuli vary more than duration estimations concerning auditory stimuli.

EPAM therefore affords us new explanations for modality effects and these explanations do not cancel each other out—if both explanations apply, then the effects they describe are cumulative. Both explanations are based on findings established independently of duration estimation tasks. Saccadic suppression, for instance, is a well-known phenomenon with confirmed mechanisms and these confirmations are merely applied to the idea of the local pacemaker (which should be accepted for good reasons). The second explanation, in turn, concerns the measured latencies of auditory and visual experiences—the states or processes on which the operation of the switch is supposedly based—rather than the switch. Thus, there is no need to postulate that the latency variability of the switch is larger for visual stimuli than auditory stimuli, for example, because the variability in duration estimations can merely be considered as a reflection of the variability in the duration of these experiences. Hence, both explanations are corroborated by findings concerning sensory processing in a context broader than duration estimation studies and, unlike the previous explanations for the findings, they are not ad hoc explanations.

Another merit of the proposed explanations for modality effects is that they make predictions that can be empirically tested. The first one can be tested straightforwardly with an eye tracker: for example, if the slope effect occurs, but the number and size of saccades remains the same throughout the presentations of visual stimuli, then the explanation based on saccades does not explain the effect. The second explanation, in turn, predicts that the features of the stimuli that influence the onset and offset latencies of visual stimuli (and the variability thereof) should have almost the same effect on duration estimations. Thus, if latencies for, say, a bright flash are smaller and show less variability than latencies for a dim flash, then the estimated duration of the first flash should be longer and show less variability than the estimated duration of the latter.

## 5. Filled-duration illusion

The filled-duration illusion refers to the phenomenon that unfilled intervals (e.g., an interval demarked by a flash at the beginning and the end) are estimated to last 35-45 percent less time than filled intervals (e.g., those with a continuous light) of the same objective duration. This illusion shows the slope effect as the difference increases (in milliseconds) with the increased duration of the stimuli. PAM explains the illusions and the modality effects in a similar way, namely by maintaining that the rate of the pacemaker is higher for filled stimuli than unfilled stimuli.[6] (Wearden et al. 2007) However, it remains unclear why the rate of the pacemaker would differ for these stimuli.

When we take the internal response to the stimuli into consideration, we can make at least some progress towards explaining the illusion. Consider, for example, the auditory version of the illusion. As discussed above, the onset and offset latency for stimuli used in duration tasks are the same for auditory stimuli when filled stimuli are used. Thus, the duration of the experience of a filled duration closely mirrors the duration of the stimuli. However, according to Efron (1970a; 1970b), auditory experiences have a minimal duration of 120-130 milliseconds. This means that when a very brief stimulus is used (say, a tone lasting 10 milliseconds as in Wearden et al. 2007) to mark an unfilled interval, the offset is perceived to occur much later than the onset and the interval begins much later than when the interval is marked with onset (as in filled-durations). Therefore, the experience of the unfilled interval is shorter than that of the interval marked with a continuous sound. This explanation is in effect Grondin's (1993) internal-marker hypothesis, one of the few examples in duration estimation research in which the properties of the internal response to stimuli have been explicitly employed in an explanation of distortions in duration estimation.

The previous explanation does not however account for the slope effect, nor for the fact that the illusion also occurs when the empty interval is marked with a longer stimulus (in these cases, the onset and offset latencies are the same). EPAM provides support for at least one explanation for these findings as well. This explanation assumes that the strength of the neural processing of continuous stimuli is stronger than the processing taking place in the absence of stimuli. One reason to believe that such a difference could exist is that object-based

[6] In addition to this explanation, another explanation for the filled-duration illusion has been presented in the framework of PAM. This explanation is based on the idea that sustained attention is required to keep the connection between the pacemaker and the accumulator open. This is more demanding when the unfilled stimuli are used. Accordingly, the connection between the pacemaker and the accumulator is broken more often for the unfilled stimuli than for the filled stimuli, which leads to less pulses reaching the accumulator when the unfilled stimuli is used. (Penney et al. 2000) Although the filled-duration illusion can be explained in this way, a proper assessment of the explanation must wait until the switch is described in more detail.

attention can enhance neural processing only in the presence of a stimulus.[7] If the rate of the pacemaker depends on the strength of the neural activation, then it directly follows that fewer pulses are generated when estimating the unfilled interval versus estimating the filled interval. This explanation could be tested by comparing the strength of the illusion when the unfilled duration is marked with different kinds of "absent" stimuli (say, a black screen versus a grey or white screen) that are likely to cause a different amount of neural processing.

## 6. Experience of duration

In the discussion above, it has been assumed that the experiences of stimuli which form the basis of our duration estimations concern non-temporal features of the stimuli—features of stimuli that we are commonly taken to be able to perceive, such as color, shape, and so on. Nevertheless, it has also been proposed—most recently by Phillips (2012; Phillips 2014)—that duration is something that we can experience with the same immediacy as colors and locations. That is, duration can appear as a content in our experiences—there is phenomenology of durations. Accordingly, it is interesting to consider how such experiences would figure into the framework of EPAM.

Before doing so, it is worth noting that the possibility of experiencing durations is often rejected. This is done by pointing out that, while we have sensory organs to perceive, say, visual stimuli, and dedicated cortical areas to process the features of these stimuli, we have neither sensory organs nor dedicated areas for temporal properties. (e.g., Gibson 1975; Fraisse 1984) This inference is unpersuasive, however, because it would follow that we do not experience simultaneity and succession either, and yet it is commonly argued by both philosophers (see Dainton 2010 for several examples) and psychologists (e.g., Piéron 1952) that we have such experiences.

The possibility of temporal experiences is also compatible with the thesis of temporal isomorphism. In fact, this thesis is neutral regarding the issue of whether we experience succession and other temporal features. This neutrality is due to the fact that the thesis only concerns the relationship between the temporal properties of experiences and the temporal properties of the neural states realizing the experiences, and the temporal properties of experiences do not necessarily determine the experienced temporal properties. For example, from the fact that my experience of morning coffee precedes my experience of afternoon tea, it does not follow that I have an experience of the tea succeeding the coffee. (Or as philosophers like to express it, the succession of experiences is not the same as the experience of succession.) Concurringly, none of the cited scientists (both for and against the thesis of temporal isomorphism) comment on whether simultaneity or succession themselves are experienced. Likewise, temporal phenomenology can be accepted by both the so-called extensionalist models of time consciousness, which are compatible with the thesis, as well as the retentionalist models, some versions of which are incompatible with the thesis. In short, the thesis of temporal isomorphism—having originated from the debate concerning performance in postdiction effect

[7] It is worth noting that the absence of stimulus is often not absolute—seeing a black screen is different than being blind and not having any kind of visual experience—and even if it were, sensory cortices exhibit spontaneous activity.

tasks—is neutral concerning the issue of whether any of the temporal properties mentioned (simultaneity, succession, and duration) figure into our experiences as contents.

There is hence no reason why duration could not be one of the properties of stimulus that we can experience. Given that EPAM distinguishes the duration of experience and the estimated duration of experience, if durations are experienced, then such experiences are likely to relate to one of them rather than be altogether separate.

According to the first option, the experience of duration is closely related to the duration of experience, making the experience of duration related to the same perceptual processes as those involved in processing colors, shapes, and so on. This option is problematic because it undermines the soundness of EPAM. For instance, if duration is something that is experienced, and thus tracked as early as the perceptual processing stage, why would a separate timing mechanism (or at least a switch and accumulator) be triggered in the later processing stages, after those in which the experience of duration is realized? What makes this even more inexplicable is that estimated duration can be very different than experienced duration, and this is because the two relate to different processes. Thus, say, we would experience an unfilled interval to last a certain amount of time, but estimate it to last 35–45 percent less than that time. This highlights yet another odd feature of this option: even if there is such a thing as phenomenology of durations, such phenomenology does not bear relevance for our estimations of duration. This is because the estimation of the duration depends on the rate of the pacemaker and how long the switch is open—the duration of the experience only influences (but does not determine) the latter. This means that experiences of duration would have a very different role in our perceptual judgments than experiences of other properties would. This is because our estimation of, say, the color or direction of a stimulus is at least thought to be based on our experience of the color and direction of the stimulus. Overall, this option does not appear tempting in the framework of EPAM.

According to the second option, the experience of duration is processed at the post-perceptual stages, at the processing stages taking place after those related to experiences (as they have been understood here). One possible interpretation of this option is that we experience the "read-outs" of the accumulator—that is, we experience the number of pulses accumulated (presumably, something that changes as the continuing experience progresses). This interpretation, which is obviously in need of much more clarification, would bind together our duration estimations with the experience of duration. Subsequently, unlike the first option, this interpretation would not undermine support for the pacemaker-accumulator model or the existence of experiences of duration. In fact, in this case, one could reasonably claim that our estimations of durations are based on experienced durations, similarly to the estimations and experiences of other properties of a stimulus. Moreover, this option would coincide with the assumption mentioned above, namely that the pacemaker-accumulator system functions based on the experiences of non-temporal features of the stimuli.

In short, I take the second option to be more plausible than the first option in the framework of EPAM. However, the second option has the consequence that the duration of experience and the experience of duration can deviate from one another since the latter depends on both the former and the rate of the pacemaker. The same consequence would also follow if "experience" is understood in the framework of the global workspace theory, because the switch would operate based on the broadcasted perceptual information within this framework as well (those which were previously experiential states would now be pre-experiential states). Furthermore, it is not clear that this consequence can plausibly be avoided in most other theories of consciousness (e.g., in Dennett's multiple drafts model) since our estimations of the duration of our experiences of stimuli are sometimes so exaggerated that the estimations cannot be (objectively) correct.

The consequence that the experience of duration does not need to concur with the duration of experience is compatible with EPAM, but incompatible with Phillips' position. This is because he subscribes to the *inheritance principle*, which states that "for any temporal property apparently presented in perceptual experience, experience itself has that same temporal property" (Phillips 2014, p.131). Understood as a claim concerning experienced temporal properties[8], the principle holds that the duration of the experience must match the experienced duration—exactly the opposite of what the second option claims above. Consequently, it appears that Phillips must either reject EPAM or that duration is in fact experienced.

Phillips would presumably opt for the first alternative, as he has indeed argued that duration estimations (or duration perceptions, as he calls them) should be understood in part relative to ongoing mental activity rather than in terms of the pacemaker-accumulator model (Phillips 2012). However, this may not allow him to avoid the problems. First, Phillips' alternative view provides a single explanation for duration estimations and estimations of the speed of time passing by (e.g., how time slows down during accidents). Yet they should be separated for empirical reasons (Wearden et al. 2014; Wearden 2015), and because the two are theoretically separate (as an analogy: the *rate* of a metronome during an interval is different than the *amount* of ticks the metronome provides). Second, as discussed in section two, our estimations of how long a stimulus lasts do not always coincide with the duration of experience. Results supporting this claim are independent of how the results are interpreted. Hence, even if one rejects EPAM and endorses some other framework, it appears that duration estimations and the duration of experiences can diverge. Accordingly, if one maintains both that we have experiences of duration and that the experience itself has the same duration as is experienced, then it is not clear that the experience of duration plays a role in the duration estimations. In this case, one can reasonably wonder why we should believe the inheritance principle or that we experience durations in the first place.

## 7. Summary

Although highly influential, the standard pacemaker-accumulator model is inadequate because it does not specify the internal response to the stimuli forming the basis on which the switch

[8] Depending on how "apparent" is understood, the definition of the inheritance principle lends two interpretations. On the one hand, the principle can concern temporal properties that are experienced. On the other hand, the principle can concern temporal properties that may appear but does not need to hold between experiences. In this interpretation, temporal property is not experiential content and the inheritance principle thus resembles the thesis of temporal isomorphism. While some of Phillips' examples explicitly describe temporal relations between different experiences, which suggests the latter interpretation, the inheritance principle should be understood along the lines of the first interpretation. This is supported by the fact that Phillips usually writes about the temporal structure of a singular experience and the fact that the principle is presented in relation to the debate concerning time consciousness (which concerns experienced temporal properties).

operates, nor does it provide (proper) explanations and predictions for our duration estimations in various experimental set-ups. A supplemented version of the pacemaker-accumulator model, the experiential pacemaker-accumulator model, was presented to amend this situation. According to this model, the operation of the switch is controlled by conscious access to the experiences of the stimuli, and the neural correlates of the experience fulfill the function of the pacemaker. The strength of these processes determines the rate of the pacemaker. These claims are compatible with the standard pacemaker-accumulator model and hence, rather than challenging the model, they can be understood as a suggested supplement describing unspecified elements of the model. Although these claims are also partly supported by studies not directly related to duration estimation, the strongest reason to ultimately endorse the experiential pacemaker-accumulator model is that it provides better explanations for the systematic errors in duration estimations than the standard pacemaker-accumulator model. Moreover, by supplementing the standard pacemaker-accumulator model in the proposed way, the model is theoretically more plausible and becomes empirically testable (and refutable).[9]

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