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Repetition, expectation, and the perception of time

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Prior experience with a stimulus profoundly affects how it is processed, perceived, and acted upon. One striking finding is that repeated items seem to last for less time than novel or rare ones. This link between the processing of stimulus identity and the perception of stimulus duration has important implications for theories of timing, and for broader accounts of the organization, purpose, and neural basis of perception. Here, we examine the nature and basis of the repetition effect on subjective duration. Contrary to unitary accounts which equate repetition effects with implicit expectations about forthcoming stimuli, new work suggests that first-order repetition and second-order repetition–expectations differentially affect the perception of time. We survey emerging evidence from behavioural studies of time perception and neuroscientific studies of stimulus encoding which support this view, and outline key questions for the future.

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The world is not completely chaotic. The same objects recur at and for regular amounts of time [1], and extracting these regularities to predict *what* will happen *when* is a core function of the nervous system [2•,3]. The effect of prior stimulus processing on the internal measurement of time therefore speaks to basic issues in cognitive and neural science, and there is a strong empirical link between repetition and time perception: stimuli which have been encoded in the recent past are perceived to last longer than rare or novel items [4,5]. Here, we discuss recent research which has illuminated the nature of this *repetition effect*, and how these findings cast new light on the neural and computational basis for subjective time.

The reality and generality of the repetition effect

The repetition effect comes in several guises [4–8]. Most commonly, it is investigated by presenting a standard stimulus (e.g., a black circle) of fixed duration several times in succession, with a deviant 'oddball' (e.g., a black square) of variable duration occurring towards the end of the stream. Participants typically judge the oddball's duration as longer than the standard's. The compression of the repeated standards relative to the oddball has been found for auditory and visual stimuli, for simple and complex stimuli, and for oddballs that deviate from the standards in their colour, movement, shape, pitch, or orientation [5,9–11].

The oddball task is problematic. It requires people to compare a single oddball with multiple standard presentations whose subjective durations may themselves vary, and it confounds novelty with sequential position (oddballs occur towards the end). Indeed, a recent study found that, when the stimuli appeared in sequence around the perimeter of an invisible circle, oddballs were judged to have the same duration as standards presented at the same point in the sequence (although the usual repetition effect was found when all items occurred in a fixed central location) [12].

An alternative, *two-interval* paradigm presents just two stimuli and compares trials where the second item is a repeat of the first to trials on which it is novel [4]. This deconfounds the effects of repetition and sequence-position, but nonetheless produces a robust repetition effect for faces, complex pictures, simple icons, and meaningless letter strings, and across a range of duration judgments and procedural variations [4,13,14•].

One recent concern is that the repetition effect may be a form of response bias or heuristic [4,15,16]. However, when participants simply classified oddballs as 'same' or 'different' from the standards (rather than shorter/longer) the point of subjective equality was still shifted, indicating that the effect involves a genuine perceptual distortion [17].

In short, the repetition effect is a robust and widespread feature of time perception — albeit with some constraints (Table 1). How is it to be explained, and what does it tell us about the nature of subjective time?

Traditional explanations

Broadly speaking, two explanations have been invoked to explain the repetition effect (Figure 1). The first appeals to the pacemaker-accumulator framework that dominates much research on timing [18–20] (Figure 1a). Specifically, rare items might increase the rate of an internal pacemaker so that more pulses are accumulated than for a

Table 1

Some boundary conditions on the repetition effect.

Finding	Implication
Icons comprised of repeated tiles were judged no different from those made up of diverse elements [14•]	Repetition has to be temporal, not spatial
Oddball effect reverses at for very brief presentations (<100 ms) [5], and some memory tasks show longer apparent durations for items previously on a study-list [70]	At the judgement stage, participants may use a 'fluency heuristic', inferring that easier-to-process items 'must' have been seen for longer
The effect is short-lived, disappearing when the inter-stimulus interval increases to 2000 ms [14•]	Basic repetition effects may reflect low-level adaptation
Temporal production/reproduction tasks have produced mixed results [4,5,14•]	Additional effects such as desire to spend longer studying novel items may also be at work
Receding-disc oddballs are not always judged longer than static standards [22,53]	Other non-temporal variables that affect time perception can overwhelm the repetition effect

repeated item. The pacemaker acceleration has been attributed to unexpected stimuli being more 'arousing' [8], and/or capturing attention and increasing the rate of information processing [5,10]. Independent measures of arousal (e.g., physiological recordings) or attentional allocation have not been attempted, so direct evidence is lacking. However, oddballs only expand subjective time at durations longer than approximately 300 ms, consistent the pacemaker needing time to accelerate [21]. Moreover, the apparent duration of a central target is increased by peripheral (asynchronous) oddballs irrespective of their spatial distance, suggesting a global expansion of subjective time [10], although the argument is weakened by the lack of cross-modal effects [11,22] and the fact that stimulus novelty produces a fixed increment in apparent duration rather than acting multiplicatively with physical time, as would be expected if there were more 'pulses per second' [4,23,24].

The second explanation is that repeated stimuli evoke smaller neural responses ('repetition suppression') and that the size of the evoked neural response — the *coding efficiency* — provides the metric of subjective time [25,26] (Figure 1b). Repetition suppression may reflect neural adaptation [27], or a decrement in the number of neurons needed to represent the item [28], but time-perception researchers have typically favoured a *predictive coding* interpretation. Under this account, the brain generates predictions about forthcoming stimuli such that activation at a given stage of processing reflects the discrepancy between incoming information and expectations that have been back-projected from later/higher stages in the hierarchy [3,29].

In support of a predictive-coding explanation, the oddball effect is greater following more repetitions of the standard [9,30] and for more deviant oddballs [9,30,31], consistent with stronger violations of expectation and mirroring the magnitude of evoked neural responses [32] (but see [9], for a more complex possibility). Similarly, oddball effects generalize across eyes whereas low-level adaptation effects such as Troxler fading do not [31]. Despite their differences, the pacemaker-based and coding-efficiency accounts share the assumption that repetition effects are a manifestation of implicit expectations: repeated stimuli seem to last for less time because they are expected.

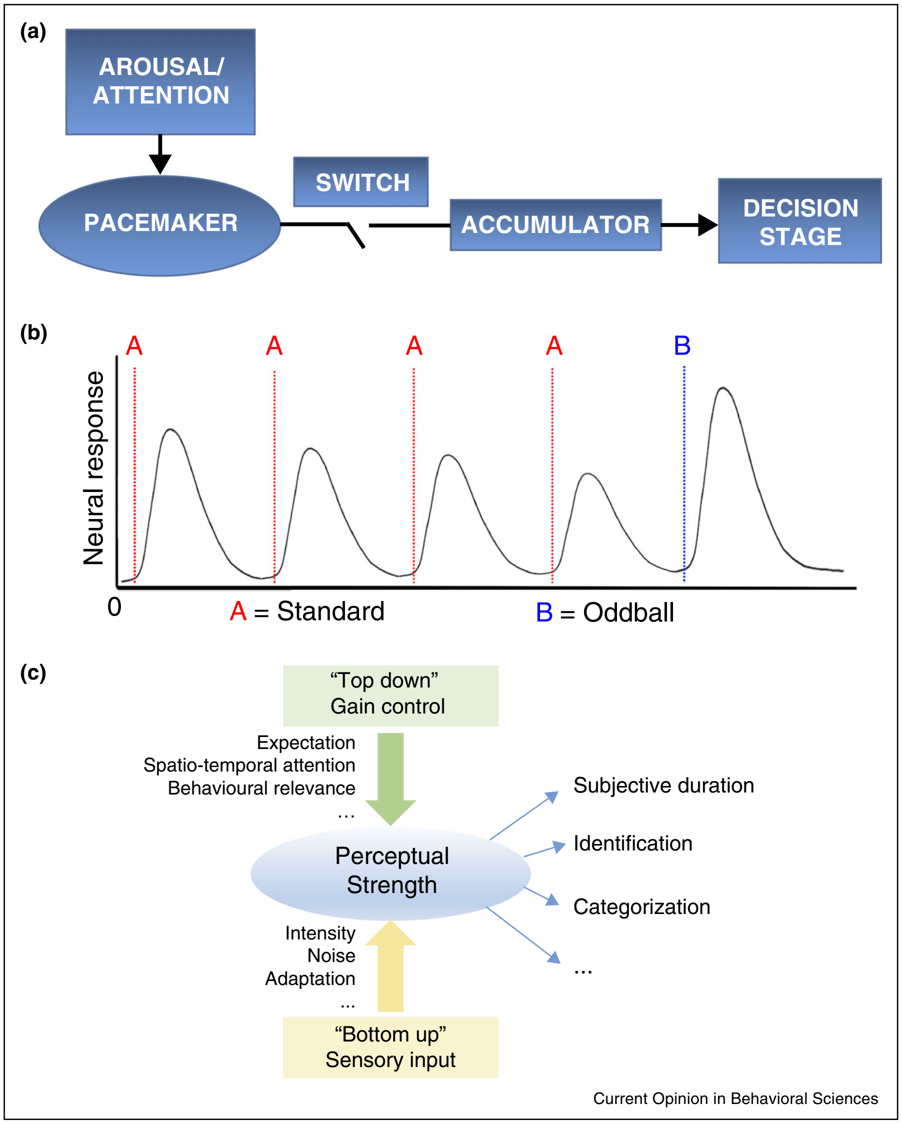
Beyond the unitary accounts: two routes to subjective time

Neuroscientists have sought to test whether repetition suppression reflects predictive coding rather than purely low-level adaptation by presenting many pairs of stimuli and varying the proportion of trials for which the second item is a repetition of the first. A 'pure' repetition effect should be independent of the repetition probability [33] (Figure 2, top row). However, if repetition suppression reflects implicit expectations, it should be more pronounced when repeats are common and novel stimuli are correspondingly even more surprising than usual (Figure 2, middle row). Initial fMRI work with face stimuli found the latter [34], and the pattern has replicated with across modalities, tasks, and imaging techniques [35–37].

Recent work has applied this approach to time perception [14•]. Participants saw pairs of faces and judged whether the second was shown for more or less time than the first. Repeats were, on average, judged longer than novel items, but this effect was *more* pronounced when repetitions were rare — exactly the opposite of an expectation-based account and the pattern seen in neuroimaging studies (Figure 2, bottom row). The effect generalized to other types of stimuli and judgement tasks, and in one experiment the usual repetition effect actually *reversed* when repetitions were common, so that repeated items were judged to last longer than novel ones.

These findings argue against a unitary account of the repetition effect and suggest that first-order repetition and second-order repetition–expectations exert opposing influences, with the former leading to compression and the latter to expansion of subjective time.

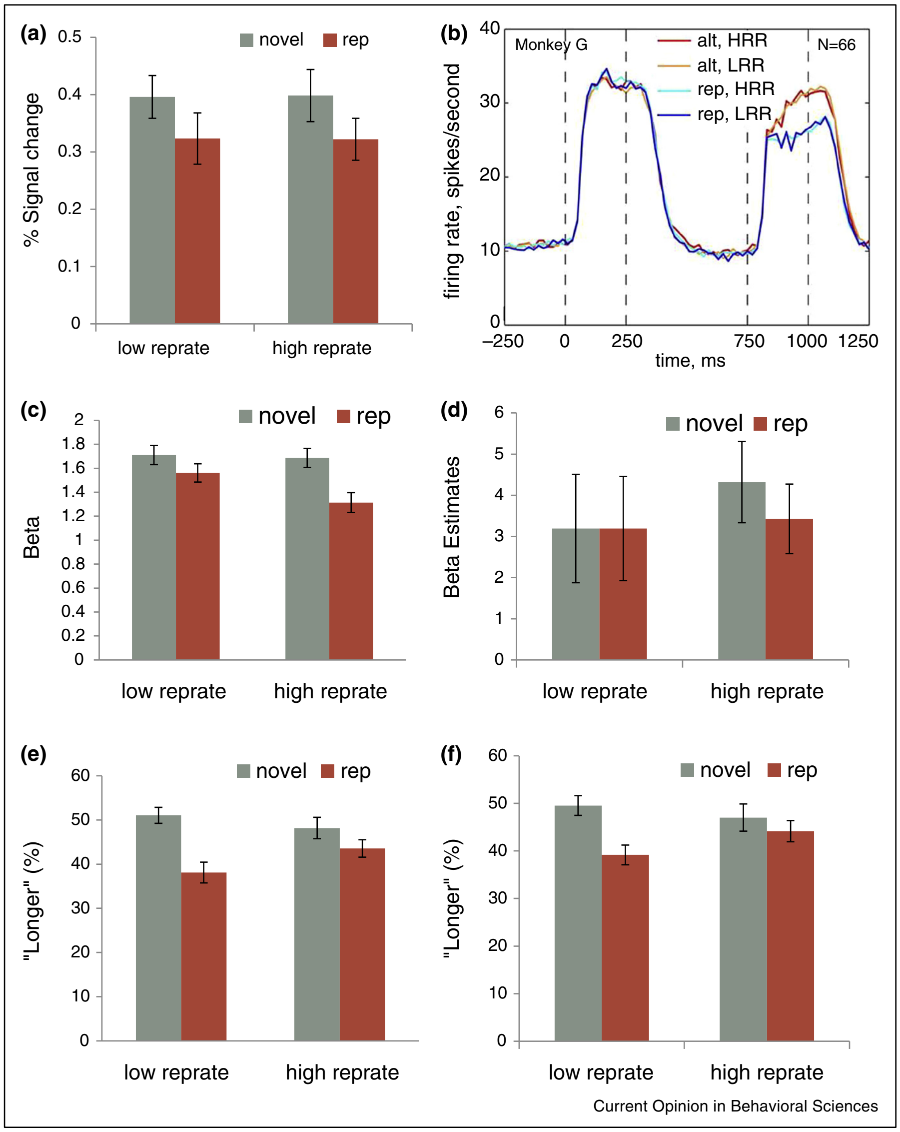
Figure 1



Three accounts of the repetition effect. **(a)** A generic pacemaker-accumulator model of timing. Novel stimuli have been posited to increase pacemaker rate by producing a surprise-driven surge of arousal or attention-based increase in information processing. **(b)** A coding efficiency framework. Successive repetitions evoke progressively smaller responses, which recover upon presentation of a different item. **(c)** A new framework. Subjective time depends on the overall strength of the percept. Repetition-induced adaptation weakens the effective signal-strength, but higher-level expectations boost the gain for relevant features. More broadly, variables such as intensity [23], salience, and directed attention [47], which facilitate stimulus identification, categorization and so forth, will also expand subjective time [49].

What might underlie these opposing effects? Recent research has shown that exposure to a low-level stimulus feature produces a spatially specific compression of apparent duration for stimuli sharing that feature [38–40]. For example, adapting to a drifting dot pattern compressed the apparent duration of subsequent stimuli at that location relative to stimuli at unadapted locations, but only when the test item drifted in the same direction as the adaptor [41]. Such effects occur for multiple features/modalities, and when the adaptor is only briefly presented [42–44]. Attempts to identify the basis for the adaptation suggest multiple loci, cortical and subcortical, throughout the processing hierarchy [41,45]. Thus, 'pure' (first-order) repetition effects in time perception may reflect the same relatively low-level adaptation effects, albeit for objects that are comprised of myriad features rather than the simple stimuli used in adaptation studies. That the repetition effect disappears after approximately 2000 ms may imply that these processes involve a basic physiological mechanism such as neural fatigue [14•].

Figure 2



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Three types of repetition–expectation interaction. Top row: repetition effects may be independent of 'higher order' expectations. Panel a shows repetition suppression (RS) for nonsense 'letters' that was unaffected by whether repetitions were common and expected (high reprate) or rare and surprising (low reprate) [61•]. Panel b plots the same pattern from cellular recordings from monkey cortex (HRR, high repetition rate; LRR, low repetition rate; alt, novel stimulus; rep, repeated stimulus; Kaliukhovic and Vogels, 2011, *Cerebral Cortex*, *21*, 1547–1558, by permission of Oxford University Press [33]). Panel c shows a situation where RS for faces was more pronounced when repetitions were predictable [34]; panel d shows the same expectation effect in RS for objects [63]. The bottom row shows opposing effects of repetition and repetition–expectation in time judgments: repeats seem shorter than novel items, but this effect diminishes when repetition is predictable, both for faces (panel e) and non-face images (panel f) [14•].

Panel c adapted by permission from Macmillan Publishers Ltd.: *Nature Neuroscience*, Ref. [34], 2008.

Meanwhile, when expectations are created by manipulations other than stimulus repetition, greater preparation expands apparent duration. Cuing the location of a forthcoming object, either exogenously (e.g., by flashing a dot at the location [46]) or endogenously (e.g., with an arrow cue; [47]) lengthens its apparent duration, as does increasing the predictability of *when* a stimulus will appear [48]. When stimuli are spatio-temporally predictable, they are processed better and seem to last longer, and to the extent that repeated stimuli are expected, they should have expanded apparent duration — *contra* the pacemaker and coding-efficiency accounts but consistent with the effects of changes in repetition rate [14•].

Thus, the repetition effect depends on the interplay between 'bottom-up' and 'top-down' processes, with apparent duration shortened by low-level adaptation but boosted by the expectation-driven direction of processing resources to relevant features (Figure 1c). When repeats are highly probable, the first item in each pair serves as a valid cue to the features of the second, and this cuing mitigates the low-level adaptation that normally compresses the apparent duration of repeated items.

These ideas fit within a broader framework in which subjective time depends on the 'perceptual strength' of the stimulus — the vividity of the representation and the ease of information–extraction [49]. Variables that weaken the effective sensory input will compress apparent duration; those that boost the signal (e.g., by increasing the gain for relevant features) will expand subjective time.

Neuroscientific advances

These conceptual developments are complemented by recent discoveries in neuroscience.

First, studies have examined the links between repetition–suppression and time judgments [50]. When human observers were shown a sequence of dot-motion stimuli, they judged an oddball with a different motion-direction to last longer than the repeated standards. When the same stimuli were presented to monkeys, cellular responses in area MT declined with each repetition of the standard but recovered for the oddball. Modelling showed how the leaky integration of these responses by higher cortical areas could turn this adaptation-based suppression into a duration code, with shorter responding for repeated stimuli [32]. More direct evidence comes from an MEG study using a two-interval task with simple visual stimuli. Repeated stimuli had both shorter judged duration and smaller onset-responses than non-repeats, and the size of the onset-responses predicted the duration judgments – a further indication that repetition suppression/adaptation compresses the apparent duration of recently encountered stimuli [51], although studies using the oddball paradigm offer different perspectives [52,53].

Elsewhere, it is becoming clear that the interplay between repetition and expectation is more complex than early work implied. An EEG study with face stimuli has found repetition suppression at parietal and central sites 300–400 ms post-onset, with only the central effect being moderated by repetition probability [36]. Likewise, MEG recording with auditory stimuli has found early (40–60 ms), intermediate (100–200 ms) and late (200+ ms) suppression effects driven by repetition, expectation, and their interaction, respectively [54•] (see also [55]). Thus, first-order and second-order expectations may modulate different stages of processing, consistent with a hierarchical predictive-coding framework [56] — although no imaging study thus far has found a pattern of activity changes that matches the behavioural effects of repetition-rate on time perception.

Finally, there is a growing appreciation that repetition does not always suppress neural responses. The converse *repetition enhancement* has long been known [57] and recent work has identified key factors that determine whether repetition suppresses or enhances the evoked responses. Specifically, enhancement is common for stimuli which are degraded or masked (e.g., [58]), and of low familiarity [59]. In addition, it has been conjectured that repetition enhancement may occur when stimulus repetitions are unexpected, or when attention is directed towards the stimulus [60•]. Perhaps relatedly, recent imaging studies have found that the effects of repetition-rate on repetition suppression may depend on stimulus familiarity [61•,62,63]. It will be crucial to see whether these moderators likewise alter the effects of repetition on time perception.

Conclusions

Repetition, expectation, and subjective time are intimately linked, and these associations provide fundamental insights into the nature and neural basis of perception. The work reviewed here suggests a number of key questions for the future:

- Can we directly map the behavioural effects of repetition and expectation onto neural data? No imaging study has yet found the repetition–expectation interaction found in time perception responses, but there is an urgent need to combine both types of measurement in unified studies. Our lab has recently made a start in this direction, but more needs to be done.
- Does the repetition effect occur in the 'real world' — with longer durations, complex stimuli, and one-off retrospective judgments? Whether effects generalize in this way is practically important, and also informs understanding of the underlying neuro-cognitive mechanisms [64,65].
- How is the repetition effect in time perception modulated by other types of expectation–manipulation? For example, recent neuroimaging has found additive (not interactive) effects of repetition and expectation when repetition and non-repetition of faces is equally likely and the gender of the first face reliably signals whether the second will be a repeat or novel [55]. Likewise, the identity of the first stimulus could reliably signal the identity of the second (B follows A), signal equiprobability for two items (B and C equally likely to follow A) or signal a completely novel item.
- Do the factors that putatively lead to neural repetition enhancement likewise modulate the effect of repetition on subjective time? For example, is the repetition effect different for familiar and unfamiliar faces?

- Can we integrate the repetition effect into formal mathematical and neural models of time perception (e.g., [66–68])? Particularly promising might be recent work in which object identity and object duration are both encoded by different properties of neural oscillators, providing a possible basis for a link between prior exposure to an item and its apparent duration [69•].

Conflict of interest

The authors declare no conflict of interest.

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