

## **Time perception: The surprising effects of surprising stimuli**

William J. Matthews

University of Cambridge

Correspondence Address:

William J. Matthews

Dept. of Psychology

University of Cambridge

Cambridge

CB2 3EB

United Kingdom

e-mail: [wjm22@cam.ac.uk](mailto:wjm22@cam.ac.uk)

## Abstract

The effects of stimulus repetition often increase when repetitions are more common (i.e., when repeats become more predictable), consistent with the idea that repetition effects reflect expectations about the recurrence of recent items. In contrast, the present experiments found a surprising pattern in which the compressed subjective duration of repeated items was reduced, eliminated, and even reversed when the frequency of repetitions was increased. Experiments 1-4b found that this pattern generalized across tasks, durations, and stimulus types; Experiments 5-9 investigated the mechanisms underlying these effects and suggest that recent exposure produces a short-lived contraction of subjective time consistent with a low-level process such as neural fatigue, whereas elevating the predictability of a repeat produces a subjective time expansion that may result from more efficient perceptual processing. These findings (a) establish the important point that first-order repetition and second-order repetition-expectations can have opposing functional effects, a possibility that has received little attention in general treatments of repetition effects, (b) run contrary to existing accounts of repetition effects in time perception, and suggest that there may be no simple mapping between apparent duration and the overall magnitude of the neural response, and (c) suggest a framework in which subjective time depends on the interplay between bottom-up signal strength and top-down gain control.

## **Time perception: The surprising effects of surprising stimuli**

The way that a stimulus is represented, processed, and evaluated, depends greatly on whether it has been encountered in the past. Repetition affects stimulus detection (e.g., Kristjánsson & Campana 2010), identification (e.g., Huber, 2008), semantic classification (e.g., Durso & Johnson, 1979; Scarborough, Cortese, & Scarborough, 1977), memory retrieval (e.g., Jacoby & Whitehouse, 1990), and affective evaluation (e.g., Zajonc, 1968). Likewise, prior exposure influences the neural response to a stimulus, with effects spanning timescales from milliseconds to days (e.g., Grill-Spector, Henson, & Martin, 2006) and ranging from altered molecular activity at the synapse (e.g., Zucker & Regehr, 2002) to changes in the overall activity of cortical networks (e.g., Gotts, Chow, & Martin, 2012).

The present work examines the effects of repetition on the experience of time, and demonstrates distinct, opposing effects of prior exposure and higher-order expectations. This pattern has important implications for models of timing, for broader debates about the role of expectation in cognition, and for the links between neural activity and perceptual experience.

### **Repetition and expectation**

There are two main views regarding repetition effects. The first is that repetition influences processing simply by virtue of prior exposure to the stimulus. That is, repetition effects are a “relatively automatic consequence of the bottom-up flow of perceptual information through sensory cortex” (Summerfield, Trittschuh, Moni, Mesulan, & Egnér, 2008, p.1004). Neurally, such a prior-exposure effect might arise because neurons which are selective for the repeated item fire less because of fatigue (e.g., De Baene & Vogels, 2010) or because the encoding becomes more sparse, with fewer neurons needed to represent the stimulus (e.g., Desimone, 1996), accounting for the widely-observed reduction in neural response upon repeated presentation of a stimulus (*repetition suppression*; e.g., Grill-Spector et al., 2006).

An alternative, increasingly popular conception attributes repetition effects to expectations -- mental states that reflect prior information about possible or probable future experiences (Summerfield & Egnér, 2009). Broadly, human cognition is seen as an adaptive Bayesian system which optimizes responses in light of previous information about the structure of the environment (e.g., J.R. Anderson & Milson, 1989; Chater & Manning, 2006; Shi, Church, & Meck, 2013; Tenenbaum, Kemp, Griffiths, & Goodman, 2011). Under this view, the first encounter with a stimulus establishes it as something that exists in the environment, a sensory possibility that may be encountered in future and which generates an expectation of such an encounter so that the stimulus will be detected/identified/classified more efficiently upon its next occurrence. Repetition effects

are thus attributed to adaptive changes in processing in light of likely future experience (e.g., J.R. Anderson & Milson 1989; Schacter, Addis, & Buckner, 2007), with cognitive responses to repeated material attuned to environmental repetition contingencies (J.R. Anderson & Schooler, 1991; R.B. Anderson, Tweney, Rivardo, & Duncan, 1997). Neurally, this expectation-based view is found in theories which attribute repetition effects to *predictive coding* (Rao & Ballard, 1999); sensory information flows through a processing hierarchy and is met at each stage by back-projected predictions from the next stage. Prediction error is gradually “explained away” by successive stages of cortical processing, with first-order expectations represented earlier and higher-level expectations encoded later (e.g., Friston, 2005; Lee & Mumford, 2003; Wacongne et al., 2011; see Huang & Rao, 2011, for a recent review), and many neuroscientists have argued that the minimization of prediction error is a fundamental principle of brain organization and activity (e.g., Bar, 2009; Huang & Rao, 2011; Lee & Mumford, 2003; Friston, 2009; for a wide-ranging discussion of these ideas, see Clark, 2013, and the subsequent commentaries). The expectation-based view of repetition effects therefore relates to far-ranging conceptualizations of cognitive and neural function.

### **Disambiguating prior exposure and expectation**

The roles of prior exposure and expectation in repetition effects can be disambiguated by varying the likelihood of stimulus repetition. In some environments, novel items are typically followed by other novel items and the expectation of repetition should be weak; in other situations, a novel item is likely to be repeated in the near future, and the repetition-expectation is high. If repetition exerts a low-level effect attributable merely to prior exposure then this effect should be independent of second-order expectations about the likelihood of repetition and, ergo, independent of the repetition frequency. This prediction is illustrated in the top left panel of Figure 1. However, if repetition effects reflect expectations then they should be more pronounced when repetitions are more likely, giving the pattern illustrated in the top right panel of Figure 1.

By varying the repetition rate, neuroscientists and psychologists have found considerable evidence for the expectation-based view. In one influential study, Summerfield et al. (2008) had participants view pairs of faces where the second image was either the same as the first or different. In some blocks, 75% of trials were repeats and only 25% were novel; in other blocks, these proportions were reversed such that stimulus repetition was rare. The authors used fMRI to measure the size of the neural response in the fusiform face area, and the results are re-plotted in the bottom left panel of Figure 1. The difference between repeat and novel trials (the repetition suppression effect) is much larger when the repetition rate (rep-rate) is high. The bottom right panel of Figure 1 plots similar results from Kovács et al. (2012).

These data argue that repetition suppression is a consequence of expectations rather than a purely low-level result of prior exposure, and this pattern has been replicated many times using EEG (Summerfield, Wyart, Johnen, & de Gardelle, 2011), longer adaptation durations (Larsson & Smith, 2012), non-face images (Mayrhauser, Bergmann, Crone, & Kronbichler, 2014), and auditory stimuli (Andics, Gál, Vicsi, Rudas, & Vidnyánsky, 2013; Todorovic & de Lange, 2012; Todorovic et al., 2011) and, for faces, occurs irrespective of whether or not the first and second images occupy the same spatial location (Kovács et al., 2012).

These neural data accord with behavioural studies in which the effects of repetition are modulated by repetition rate. For example, the facilitatory effects of prior exposure on perceptual identification increase when previously-encountered stimuli are more prevalent in the test set (e.g., Jacoby, 1983). Likewise, with clearly-visible primes, semantic priming is stronger when the proportion of related primes is high (e.g., Neely, 1991), and similar prime-validity effects have been found when masked repetition primes facilitate word naming (Bodner & Masson, 2004), lexical decision (Bodner & Masson, 2001), and number judgments (Bodner & Dypvik, 2005). These repetition effects have usually been taken to indicate that expectancy-based recruitment of recently-encoded experiences facilitates subsequent processing of probable stimuli (but see Kinoshita, Forster, & Mozer, 2008).

A minority of neuroscientific studies have found repetition effects that are independent of repetition probability. In particular, Kaliukhovich & Vogels (2011) found no modulation of repetition suppression by repetition probability when making electrophysiological recordings from macaque inferotemporal cortex, suggesting a “low level”, prior-exposure effect (e.g., due to neural fatigue) rather than an expectancy-based reduction in prediction error (see also Kovács, Kaiser, Kaliukhovich, Vidnyanánzky, & Vogels, 2013), and recent work suggests that familiarity may be one moderator of the expectation effect (Grotheer & Kovács, 2014). Again, these neural data have behavioural analogues. For example, the perceptual “priming of pop-out” that occurs for recently-encountered visual features seems to reflect the recency of the item rather than expectations based on environmental contingencies (e.g., Maljkovic & Nakayama, 1994).

In short, there is considerable evidence in support of a unitary, adaptationist/Bayesian framework, wherein the neural and functional consequences of repetition are attributable to top-down expectations about forthcoming stimuli, although there are some instances of first-order effects which are unmodulated by repetition probability. These two possibilities dominate neuroscientific and psychological treatments of repetition effects.

There is, however, a third possibility: prior exposure and expectation could, in principle, exert opposing effects. For example, recent exposure to an item might suppress the neural or perceptual

representation of that item, but increasing the probability/expectation of such a repeat might enhance the response to the stimulus, resulting in a repetition effect which is large when repeats are rare but which is reduced when repeats are common.

This possibility has received little attention, and would provide an important refinement to our thinking about the nature of repetition effects. As outlined below, temporal perception might be one experience for which first-order repetition and second-order repetition-probability act in opposition.

### **The effect of repetition on subjective duration**

The perception of time is influenced by many non-temporal factors (Eagleman, 2008; Matthews & Meck, 2014) and the neural and information-processing bases for time perception have been extensively studied (see Allman, Teki, Griffiths, & Meck, 2013, and Merchant, Harrington, & Meck, 2013 for recent reviews). One of the most robust effects is that repeated presentation of a stimulus shortens its apparent duration relative to novel or rare items. This is observed when a single occurrence of an “oddball” stimulus is inserted after a series of repeated standards (New & Scholl, 2009; Pariyadath and Eagleman, 2007, 2012; Schindel, Rowlands, & Arnold, 2011; Seifried & Ulrich, 2010; Tse, Intriligator, Rivest, & Cavanagh, 2004), when there are just two stimuli on each trial and the second is either a repeat of the first or a novel item (Matthews, 2011c), and when stimulus frequency is varied across trials (Ulrich, Mitschke, & Rammsayer, 2006). Moreover, the first presentation in a train of repeated stimuli is judged longer than subsequent occurrences (Rose and Summers, 1995). The compressed subjective duration of repeated items applies in both visual and auditory modalities (e.g., Kim & McAuley, 2013; Tse et al., 2004) and generalizes across judgment tasks (Birngruber, Shröter, & Ulrich, 2014; Tse et al., 2004), which has been taken to indicate a “genuine” perceptual distortion rather than a judgment artefact.

Early theorizing attributed the repetition effect to attentional capture by the unexpected, novel item, such that an oddball will seem to last longer than a repeated stimulus because “it triggers an increase in perceptual information processing” (Tse et al., 2004, p. 1187). A natural interpretation of this proposal is that the information processing rate corresponds to the efficiency with which non-temporal stimulus features are analysed, but this idea is challenged by the finding that directing attention to the non-temporal properties of an item enhances the processing of these features but *reduces* subjective duration. (e.g., Casini & Macar, 1997; Macar, Grondin, & Casini, 1994).

A second attentional account has been offered by Kim and McAuley (2013). Adopting the *dynamic attending* framework (M.R. Jones & Boltz, 1989; Large & M.R. Jones, 1999) and studying auditory oddballs, these authors suggest that the pitch- and temporal relations between oddballs

and standards across trials generate expectations about future events, with less expected stimuli being detected faster and, correspondingly, having longer apparent durations.

A third suggestion is that novel stimuli briefly elevate the observer's arousal, accelerating the rate of an internal pacemaker used for interval timing (New & Scholl, 2009; Ulrich et al., 2006). The fact that the repetition effect only emerges at durations longer than about 300-ms has been taken as evidence for this view (Seifried & Ulrich, 2010), on the basis that it takes some time for the pacemaker to speed-up (e.g., Matthews, Stewart, & Wearden, 2011).

A final proposal is that subjective time is a direct consequence of the size of the neural response evoked by the stimulus. Eagleman and Pariyadath (2009) have noted that many manipulations which increase subjective duration – including increased intensity/contrast, numerosity, and movement – also evoke larger neural responses. They suggest that apparent duration is a positive function of the energy expended on encoding the stimulus, and attribute the repetition effect on time perception to the repetition suppression that results from predictive coding (see also Matthews, 2011c; Schindel et al., 2011). Support for this idea is provided by Noguchi and Kakigi (2006), who found that the onset of repeated stimuli evoked smaller responses than non-repeats, and that this difference correlated with changes in subjective duration (see also Sadeghi, Pariyadath, Apte, Eagleman, & Cook, 2011, for a less direct demonstration, and Matthews et al., in press, for a review of recent work in this area).

### **Time perception as a candidate for opposing effects of repetition and expectation**

The attention, arousal, and predictive-coding accounts share the assumption that the repetition effect in time perception arises because novel or rare stimuli are less expected than repeated items. As such, they mirror the more general expectation-based/Bayesian accounts of repetition effects described above, and share the prediction that increasing repetition frequency will exacerbate the repetition effect such that repeats will have even shorter subjective duration relative to novel, unexpected stimuli – the pattern illustrated in the top right of Figure 1 and seen in many studies of neural repetition suppression. An alternative possibility, not much discussed in studies of time perception but apparent from the foregoing discussion of repetition effects, is that prior exposure may compress the subjective duration of repeats in a way which is independent of higher-order contingencies.

There is, however, reason to expect a different pattern. Historically, theoretical treatments of time perception have emphasized a central timing system, often conceptualized as a “pacemaker” whose pulses are accumulated during stimulus presentation to form the raw units of temporal perception (Creelman, 1962; Gibbon, Church, & Meck, 1984; Treisman, 1963; Wearden, 1992; Zakay & Block, 1997). However, there has been increasing interest in the idea that there may be multiple

“clocks” for timing distinct stimuli (e.g., Buhusi & Meck, 2009) and more generally that timing may at least partly depend on localized circuits, with temporal information encoded in the dynamics of neural activity in networks which are not dedicated timekeepers (Buonomano & Maas, 2009; Ivry & Schlerf, 2008; Mauk & Buonomano, 2004). One possibility is that time perception involves an interplay between core mechanisms and local systems (Merchant, Zarco, & Prado, 2008; Merchant et al., 2013).

The idea that timing involves local networks feeding information to central systems raises the possibility of distinct effects of “low-level” factors and “top down” influences on time perception. Importantly, there is reason to think that low-level consequences of prior exposure (repetition) and top-down influences of expectation (making repetitions more probable) may exert opposing effects.

Regarding low-level effects of prior exposure, recent work has shown that adapting to basic visual features leads to spatially-specific duration compression for those features. For example, Curran and Benton (2012) found that adapting to a moving dot kinetogram for 30 seconds compressed the apparent duration of a stimulus with the same direction of movement presented in the same hemifield. Whether such spatially-specific adaptation effects are retinotopic or craniotopic, and whether they are cortical or pre-cortical in origin, remains controversial (Bruno, Ng, & Johnston, 2013; Burr, Tozzi, & Morrone, 2007; Burr, Cicchini, Arrighi, & Morrone, 2011; Johnston, Arnold, & Nishida, 2006). Nonetheless, they indicate that recent exposure to a stimulus feature can exert relatively “low level” compressive effects on subjective time, perhaps independent of higher-order expectations.

In parallel to this is work suggesting that, contrary to the expectation-based accounts of the repetition effect outlined above, increases in the predictability of a repeated stimulus will produce an *expansion* of subjective time. As a general principle, when participants are asked to time a given stimulus or activity, the judged duration is typically longer when “executive” processing resources are available (see Block, Hancock, & Zakay, 2010, for a meta-analytic review). To the extent that predictability allows resources to be directed to timing, expected stimuli may have longer subjective duration. As a more specific effect, cuing the sensory modality or spatial location of a to-be-judged stimulus lengthens its apparent duration, an effect which becomes more pronounced as cue validity increases (e.g., Mattes & Ulrich, 1998), providing a direct demonstration that predictability lengthens apparent duration. Generalizing these effects to manipulations of repetition frequency suggests that increasing the repetition-rate will render the identity of repeated items more predictable and, by analogy with modality or spatial cuing, will serve to prolong subjective duration.

Taken together, these theoretical and empirical developments suggest that time perception may demonstrate functionally opposite effects of first- and second-order expectations, with a “low

level” prior exposure effect shortening the apparent duration of a repeated item but a “high level” expectancy effect that increases the apparent duration of repeats as the repetition-rate increases, by virtue of their greater predictability. This possibility stands in contrast to existing accounts of the repetition effect in time perception, and to broader theoretical frameworks which attribute the neural and functional consequences of repetition to an equivalency between repetition and implicit expectation, or which posit low-level effects of prior exposure that are independent of repetition probabilities. Such a dissociation would refine theoretical accounts of time perception, and would inform broader debates about the functional consequences of prior exposure, expectation, and repetition suppression.

### **The current work**

In the present experiments, participants were presented with pairs of images where the second was either a repeat of the first or novel, and where the frequency of repetitions varied between blocks of trials. Experiment 1 provides an initial test of whether repetition frequency modulates the repetition effect by using a comparison task in which the second image is judged shorter/longer than the first. Experiments 2a and 2b generalize the findings to a situation where comparison of the two images is not required; Experiment 3 employs a range of longer durations; and Experiments 4a and 4b use non-face stimuli. To anticipate: contrary to studies of repetition suppression, and contrary to extant theoretical accounts of the repetition effect in time perception, repetition exerts a larger effect when repetitions are rare. Indeed, the repetition effect was sometimes abolished or even reversed when repeats were common, consistent with opposing effects of prior exposure and expectation.

The subsequent experiments explore the mechanisms underlying this pattern. Experiments 5 and 6 find that the basic repetition effect depends on the inter-stimulus interval and on whether stimulus elements are repeated within- or between-stimuli. Experiments 7, 8, and 9 examine the mechanisms behind the effects of repetition frequency, first showing that the effect of stimulus predictability depends on the way that expectations are manipulated and then examining the effects of repetition rate on the latency to detect and semantically classify repeated/novel images, thereby providing further clues to the processes underlying the effects of repetition and expectation on the perception of time.

## General Method

In all experiments, two images were presented consecutively on each trial. On *repeat* trials, the second image was identical to the first; on *novel* trials, it was different. Most experiments manipulated the frequency of repetitions: in *high rep-rate* blocks, the majority of trials were repeats and a minority were novel; in *low rep-rate* blocks, the reverse was true.

Most experiments used a pool of 622 colour photographs of male and female faces of varying ages and ethnicities taken from databases assembled by Burton, White, and McNeill (2010), Ebner (2008, who used a subset of images from Minear and Park, 2004, see <http://agingmind.utdallas.edu/facedb>), and O'Toole et al. (2005). The images taken from these databases were all forward-looking with nominally neutral expressions, but differed in background colour, amount of visible hair, and size; they were edited to be on a white background and of approximately equal size (about 300 x 400 pixels). The images were presented against a white background on 17" inch CRT monitors (1024x768 pixels, 85 Hz) viewed through the glass window of sound-attenuating chambers from a viewing distance of approximately 80 cm (not fixed). Some experiments used non-face photographs. These were a pool of 622 colour photographs selected from those used by Matthews (2011c), depicting varied content (nature scenes, machinery, furniture, plants, etc) subject to the restriction that none contained a face. These images measured 343x245 pixels and were presented on a white background. Experiments 5 and 6 used abstract stimuli, described below.

The participants were members of the University of Essex participant panel and were paid £4 for sessions lasting approximately 30 minutes. Fresh participants were recruited for each experiment that used a given stimulus type (faces/non-face photographs/abstract images). Stimulus presentation was controlled by DMDX (Forster & Forster, 2003). All presentation times were whole numbers of screen refreshes, which explains the slightly odd millisecond values in some cases.

Manipulating repetition frequency limits the number of trials that provide data for the "rare" stimulus type, thereby inflating the number of experimental trials that are required to provide sufficient data for each cell of the design. For example, consider a 2 (stimulus type: novel vs repeat) x 2 (rep-rate: 25% repeats vs 75% repeats) within-subjects experiment. In order to obtain 30 trials for the novel stimuli in the high rep-rate condition and for the repeat stimuli in the low rep-rate condition, one needs 240 trials and 360 different face stimuli (in all experiments, the same image was never repeated across trials). Exploring a range of durations (or levels of some other factor) therefore rapidly necessitates a prohibitive number of standardized face images. The approach taken in most experiments described here was therefore to concentrate on a single "test" duration

but to include a small number of “easy” trials with much shorter/longer durations to ensure that participants were motivated to attend to temporal information, and to check that they understood the temporal judgment task. Data from these easy trials were only used to ensure comprehension/attention and were not part of the main analysis.

Participant recruitment was based on the sample size needed to obtain approximately 80% power (typically higher). Although minimum required sample sizes were fixed in advance of data collection, the vagaries of excessive sign-ups/dropouts/participants failing to complete the task etc meant that the final sample sizes were not completely pre-determined. In some cases (e.g., the preliminary experiment for Experiment 1) the relevant effect size estimates were based on previous published work or earlier experiments in the current series; in other cases, a generic “medium” effect size (e.g.,  $d = .5$ ) was assumed.

## Experiment 1

Experiment 1 provides a first investigation of whether effects of stimulus repetition depend on repetition frequency. A preliminary study was conducted in which repetition frequency was held constant at 50% throughout the task. This provided a check that the stimuli and task used here would replicate the finding that novel images are judged longer than repeats when the two are equally likely (e.g., Matthews, 2011c). In the main experiment, participants completed alternating blocks of trials with low rep-rate (25% repetitions) and high rep-rate (75% repetitions).

### Method

**Participants.** The preliminary study used 21 participants (12 female) aged 20-42 ( $M = 26.4$ ,  $SD = 5.7$ ). The main experiment actually involved two sets of participants. In the first instance, 38 participants were tested. The results were highly surprising, so some weeks later I ran an exact replication study to check whether the findings were robust, using 32 new participants (a sample size based on a power calculation using the effect size from the first set of participants). The results for this replication matched the original findings, so the data are reported here as a single set comprising 70 participants (18 male, ages 17-42,  $M = 22.9$ ,  $SD = 4.3$ ).

**Design and Procedure.** On each trial, participants saw two consecutive faces and judged whether the second (the comparison) was presented for more or less time than the first (the standard, which was always shown for 506 ms). There were six blocks of trials. Each block comprised 40 “test” trials (for which the standard and comparison faces had the same duration) and 8 “easy” trials, four where the comparison duration was much shorter than the standard (247 ms) and four

where it was much longer (1000 ms). Given the typical Weber fraction for time (e.g., Grondin, 2012), these short/long durations should be readily discriminable from the 506-ms standard and, as noted above, provide a check on comprehension and attention to the task; the primary focus is on the test trials.

In the preliminary experiment, the standard and comparison images were identical for half of the trials (repeat trials); for the other half, the comparison face was different from the standard face (novel trials). Standard and comparison faces were drawn without replacement from the pool of 622 face images such that no image was used on more than one trial. Thus, each participant saw a total of 288 (trials)  $\times$  1.5 (mean number of different faces per trial) = 432 faces. The order of the trials in each block was random. The sequence of events on each trial was: a blank interval randomly drawn from 882-1118; the standard face; a blank inter-stimulus interval (ISI) for 306 ms; the comparison face; blank interval until response (see Fig 2). Participants responded by pressing "S" if they thought the duration of comparison image was shorter than the standard and "L" if they thought it was longer. Prior to the 6 test blocks participants completed 6 practice trials (one test, one short-easy, and one long-easy trial for each of the repeat and novel conditions) using non-facial stimuli. The instructions emphasized that the task was difficult and that participants should "go with their subjective impression".

The main experiment was identical except that the 6 blocks alternated between high rep-rate and low rep-rate conditions. In the high rep-rate blocks, three quarters of the trials were repeats and one quarter were novel; in the low rep-rate blocks the proportions were reversed. Thus, for example, there were 10 repeat test trials per low rep-rate block, giving 30 repeat test trials in low rep-rate blocks across the whole experiment. Odd-numbered participants started with a low rep-rate block; even-numbered participants started with a high rep-rate block.

## Results

**Preliminary experiment.** Two participants were excluded for failing to achieve 80% correct on the easy trials (the mean for the remaining participants was 95.3%). The main analysis concerned the proportion of "longer" responses for the test trials in each condition.

The experiment replicated the typical repetition effect: the proportion of "longer" responses for novel faces ( $M = 50.09\%$ ,  $SD = 15.83\%$ ) was significantly greater than for repeats ( $M = 34.65\%$ ,  $SD = 12.07\%$ ), paired-sample  $t(18) = 4.64$ ,  $p < .001$ . Moreover, for the repeat trials the proportion of longer responses was significantly below 50%,  $t(18) = 5.54$ ,  $p < .001$ , whereas for the non-repeats it was not,  $t(18) = .02$ ,  $p = .981$ . That is, when the comparison image was a repeat of the standard it was judged shorter than the standard, but when it was novel it was judged equal to the standard.

**Main experiment.** Five participants were excluded for making more than 20% errors on the easy trials (mean error rate for the remaining participants = 3.4%) leaving a sample of 65 (33 who started with a low rep-rate block and 32 who started with a high rep-rate-block).

The mean proportions of “longer” responses for each condition are plotted in the top left panel of Figure 3. A 2x2 within-subjects ANOVA confirmed the impression from the figure: novel items were, on average, judged longer than repeats,  $F(1, 64) = 24.15, p < .001, \eta_p^2 = .27$ , but this effect was modulated by the frequency of stimulus repetitions,  $F(1,64) = 21.23, p < .001, \eta_p^2 = .25$ . There was no overall effect of rep-rate,  $F(1,64) = 1.33, p = .253, \eta_p^2 = .02$ .

The top right panel of Figure 3 shows the effect of novelty vs repetition for the low and high rep-rate conditions, and between low vs high repetition rates for novel and repeated stimuli. The difference between repeats and novel stimuli was larger when repetitions were rare. Furthermore, rep-rate primarily influenced the judgment of repeated items: raising the repetition frequency had no significant effect on the judgment of novel faces, but increased the probability of a “longer” response to repeats.

## Discussion

The results of Experiment 1 are surprising. The preliminary study and low rep-rate conditions replicate the usual finding that novel stimuli are judged longer than repeats. However, when repeats were frequent, this effect diminished, primarily because the subjective duration of repeated items increased. This effect of repetition rate on subjective time is the opposite of that found in studies of repetition suppression, where the reduced neural response to repeated stimuli is *exacerbated* when repetitions are common (compare Figure 3 with the bottom panels of Figure 1).

Experiment 1 therefore provides an unusual result, and suggests that both prior exposure *per se* and stimulus expectations contribute to the effect of repetition, but with opposing effects. As noted, if the repetition effect were purely due to prior exposure, it would not be modulated by repetition rate; if it were purely driven by expectations, making the predictable (i.e., repeated) stimuli more predictable ought to exaggerate the effect. In fact, the difference between novel and repeated items diminished with increasing repetition rate.

In short, the current pattern is distinct from the two possibilities usually discussed in general treatments of repetition effects (i.e., that the effect will be independent of repetition rate, or that increased rep-rate will exacerbate the effect; see the top panels of Figure 1), contradicts the expectation-based views advanced in time-perception studies, and suggests a dissociation between

subjective duration and the overall size of the neural response. The next five experiments sought to replicate, clarify, and explore boundary conditions on these findings.

### Experiment 2a

Experiment 2 examined whether the surprising results of Experiment 1 generalize to a different judgment task. In Experiment 1, participants compared the durations of the first and second image on each trial. This may have made the similarity relation between the two images especially salient; neuroimaging studies of the effects of rep-rate on repetition suppression have not required this kind of explicit comparison (e.g., Summerfield et al., 2008), which might underlie the apparent dissociation between the neural-activity data and the present findings. Similarly, the test trials of Experiment 1 required a shorter/longer judgment when the comparison was, in fact, equal to the standard. This situation of maximal uncertainty increases the effects of non-temporal factors but may also encourage the use of judgment heuristics which might be distinct from the purely “perceptual” effects of repetition and novelty (e.g., Birngruber et al., 2014; Matthews, 2011c). More generally, the linguistic categories “shorter” and “longer” may influence how people construe a magnitude comparison (Matthews & Dylman, 2014) and in turn influence their decision rule (Birngruber et al., 2014).

Experiments 2a and 2b therefore used a task which did not require explicit comparison of the first and second image, and where participants were free to indicate that repeat and novel images were shown for the same duration. Specifically, the stimuli and structure were identical to Experiment 1, but participants classified the duration of the second image on each trial as being one of 5 durations.

### Method

As before, a preliminary experiment was conducted in which the rep-rate was 50% in all blocks, to check whether the new judgment task would replicate the typical finding that repeated images are judged shorter than novel ones when both are equiprobable. In the main experiment, rep-rate alternated between blocks with exactly the same trial structure as Experiment 1.

**Participants.** Eighteen participants completed the preliminary experiment (5 male, aged 19-22,  $M = 20.9$ ,  $SD = 1.3$ ). Thirty nine participants completed the main experiment (16 male, ages 18-29,  $M = 20.7$ ,  $SD = 2.5$ ).

**Design and Procedure.** The preliminary and main experiments were identical to those of Experiment 1, except for the task requirement. Participants classified the second image of each pair

as one of 5 durations, labelled 1-5. At the start of the experiments, participants were shown a grey square (350 x 350 pixels) for one presentation at 247, 353, 506, 718, and 1000 ms, in order of increasing duration, with the durations labelled “Time 1” to “Time 5”. (Each duration was approximately 1.4 times longer than the preceding one.) They initiated each exposure with a spacebar press in response to a prompt; there was a one second blank screen between the spacebar press and the grey square, and a further one second blank after the square had disappeared and before the next prompt/instructions appeared. During the task, participants pressed the number keys 1-5 at the top of the keyboard to indicate which of the 5 times the second image had been shown for. (Note that only durations 1, 3, and 5 were presented during the experiment, with the large majority being #3; it was not expected that participants would accurately memorize the five durations; rather, they served to provide a rough set of anchors for a 5-point category-rating scale.)

## Results and Discussion

**Preliminary study.** As in Experiment 1, the 247- and 1000-ms stimuli were only included as attention/comprehension checks; all participants judged the 1000-ms stimuli as longer than the 247-ms stimuli. For the test trials, a paired-t-test showed that the mean category judgment for the novel images ( $M = 2.27$ ,  $SD = 0.44$ ) was significantly higher than that for repeated images ( $M = 2.12$ ,  $SD = 0.42$ ),  $t(17) = 2.25$ ,  $p = .038$ . That is, novel stimuli were judged longer than repeats, as before.

**Main experiment.** One participant was excluded because their mean judgments for the 1000-ms stimuli were smaller than those for the 247-ms stimuli, leaving 38 participants (19 with the low rep-rate for the first block and 19 with high rep-rate for the first block).

The mean judgments of the 506-ms faces are plotted in the middle left panel of Figure 3. A 2 x 2 within-subjects ANOVA revealed no overall effect of rep-rate,  $F(1,37) = 0.06$ ,  $p = .804$ ,  $\eta_p^2 = .00$ , but a significant overall tendency to judge novel items as longer than repeated ones,  $F(1,37) = 28.23$ ,  $p < .001$ ,  $\eta_p^2 = .43$ . This tendency which was more pronounced in the low rep-rate blocks, but the interaction missed significance,  $F(1,37) = 3.83$ ,  $p = .058$ ,  $\eta_p^2 = .09$ .

Experiment 2a replicated the qualitative pattern of Experiment 1 in finding that the relative expansion of subjective duration for repeated stimuli was reduced when repeats are common, but the interaction between the effect of stimulus repetition and repetition frequency was smaller and missed significance. Experiment 2b sought to strengthen the effect by having longer runs of trials at each rep-rate (Summerfield et al., 2011). Rather than alternating blocks having low and high repetition frequency, participants completed three consecutive blocks with a low rep-rate followed by three with a high rep-rate, or vice-versa.

## Experiment 2b

### Method

**Participants.** Thirty five participants completed the experiment (6 males, ages 17-29,  $M = 20.9$ ,  $SD = 2.4$ ), 18 with the low rep-rate trials before the high rep-rate trials and 17 in the reverse order.

**Design and Procedure.** The experiment was identical to Experiment 2a except that the three blocks with a given rep-rate occurred consecutively.

### Results and Discussion

The mean judgments of the 506-ms faces are plotted in the bottom left panel of Figure 3. A 2x2 within-subjects ANOVA confirmed the visual impression: overall, novel items were judged longer than repeats,  $F(1,34) = 15.58$ ,  $p < .001$ ,  $\eta_p^2 = .31$ , but this effect was qualified by the interaction with rep-rate,  $F(1,34) = 50.98$ ,  $p < .001$ ,  $\eta_p^2 = .60$ ; there was no main effect of rep-rate,  $F(1,34) = 0.21$ ,  $p = .653$ ,  $\eta_p^2 = .01$ .

The contrasts plotted in the bottom right panel of Figure 3 show the effects of repetition at each rep-rate and the effect of rep-rate for repeated and novel stimuli. As can be seen from the 95% confidence intervals, and replicating the pattern in Experiment 1, novel stimuli were only judged longer than repeats when repetitions were rare. Also as in Experiment 1, increasing the frequency of repetitions significantly increased the perceived duration of repeat stimuli; in addition, increasing the frequency of repetitions significantly reduced the judged duration of novel stimuli, although this effect was smaller than the effect on repeated images.

The change in the block structure from Experiment 1 was intended to increase the size of the rep-rate effect. The estimated effect size for the interaction between stimulus type (novel, repeat) and rep-rate is indeed much higher than in Experiment 2a, and a cross-experiment comparison lends support to this: a 2 (rep-rate) x 2 (stimulus type) x 2 (experiment) mixed ANOVA produced a significant three-way interaction,  $F(1,71) = 12.92$ ,  $p = .001$ ,  $\eta_p^2 = .15$  (although there is significant inequality in the covariance matrix, so some caution is needed).

Does the effect of repetition frequency require the participant to have experienced both low- and high repetition rates in the experimental session? Analysis of just the first 3 blocks of trials from each participant (i.e., those for which the rep-rate is either low or high, with rep-rate now a between-subjects factor) suggests not: a 2x2 mixed ANOVA revealed the same pattern as the within-subjects analysis. That is, novel items were judged longer than repeats,  $F(1,33) = 12.85$ ,  $p = .001$ ,  $\eta_p^2$

= .28, and this effect was qualified by rep-rate,  $F(1,33) = 16.88, p < .001, \eta_p^2 = .34$ , with no main effect of rep-rate,  $F(1,33) = 0.07, p = .793, \eta_p^2 = .00$ .

Experiments 2a and 2b replicate the interaction found in Experiment 1: when repetitions are common, the difference between the subjective duration of repeated and novel faces is greatly reduced. The modulating effect of repetition frequency does not depend on explicit comparison of the two images, applies in a judgment task where participants are free to judge the novel and repeated stimuli as being the same duration, and applies when rep-rate is varied between-subjects.

The next experiment examines these effects at a range of longer durations, and employs a socially-agreed judgment scale (seconds) which obviates the need to encode a particular standard duration.

### Experiment 3

#### Method

**Participants.** Forty two participants completed the experiment (17 male, aged 19-45,  $M = 26.1, SD = 6.7$ ); two additional participants were discarded, one because he fell asleep and another because she was familiar with the face stimuli, having used some of them in an experiment of her own.

**Design and Procedure.** On each trial, participants saw two faces which were either identical or different. Low rep-rate blocks comprised 12 repeat trials and 36 novel trials; the reverse was true in the high rep-rate blocks. Low- and high rep-rate blocks alternated throughout the experiment with alternating participants starting with the low/high rep-rate conditions, as in Experiment 1.

The first image on each trial was shown for 506 ms; the second was shown for one of three durations: 906, 1000, or 1094 ms. Each duration was used for one third of the repeat trials and one third of the novel trials within each block. Participants judged the duration of the second face on a seven point scale ranging from 0.7-1.3 seconds in 0.1 second increments.

The sequence of events on each trial was: blank interval for 882-1118 ms; first face for 506 ms; blank for 306 ms; second face for 906, 1000, or 1094 ms; blank interval until response. Participants indicated their judgment by pressing one of 7 labelled keys along the top of the keyboard. They completed a practice set of 6 trials (3 novel and 3 repeat trials at each duration) prior to the main task.

#### Results

The mean judgments and standard deviations for each cell of the design are shown in Table 1. A 3 (duration: 906, 1000, 1094 ms) x 2 (rep-rate: low vs high) x 2 (stimulus type: novel vs repeat) within-subjects ANOVA showed that (as one would expect) judgments were larger for faces that were presented for longer,  $F(1.39, 57.16) = 127.12, p < .001, \eta_p^2 = .76$  (Huynh-Feldt correction applied). There was no overall difference between repeated and novel faces,  $F(1,41) = 1.07, p = .306, \eta_p^2 = .03$  and no overall difference between the high rep-rate and low rep-rate blocks,  $F(1,41) = 0.01, p = .926, \eta_p^2 = .00$ . However, there was an interaction between stimulus type and the rate of repetition,  $F(1,41) = 5.80, p = .021, \eta_p^2 = .12$ . This two-way interaction is illustrated in the left panel of Figure 4; the right panel plots the pairwise contrasts. As can be seen from the 95% confidence intervals, there was no difference between the subjective duration of novel and repeated faces in the low rep-rate blocks, but when repetitions were common, repeated faces were judged to last longer than novel ones. Changes in rep-rate did not significantly change the judged duration of either novel or repeated items.

Neither the interaction between rep-rate and duration nor the three-way interaction with stimulus type were significant,  $F(2,82) = 0.04, p = .962, \eta_p^2 = .00$  and  $F(2, 82) = 0.02, p = .980, \eta_p^2 = .00$ , respectively, but there was a two-way interaction between repetition-status and duration,  $F(2, 82) = 5.91, p = .004, \eta_p^2 = .13$ . The latter arose because repeated stimuli were judged longer than novel ones for the 1000-ms duration,  $t(41) = 2.59, p = .013$ , but not for the 906-ms or 1094-ms stimuli,  $t(41) = 1.28, p = .209$  and  $t(41) = 1.39, p = .171$ , respectively. Notably (and like Matthews, 2011c), this study did not find a steady increase in the repetition effect with increasing duration, contrary to the what would be expected if repetition affected the rate of an internal pacemaker.

## Discussion

Experiment 3 replicated the interaction found in Experiments 1-2b, using longer durations and a different judgment task. Experiments 1-2b found longer judgments for novel stimuli when repetitions were rare, and this effect diminished or disappeared as repetition rate increased. Experiment 3 found no effect of repetition when repetitions were rare, and actually found longer subjective duration for repeated stimuli when repetitions were frequent. In other words, the change in duration (or task) has “shifted” the interaction along such that, looking across all experiments, there is a cross-over. The finding that immediately repeated stimuli are sometimes judged longer than novel ones has not been reported before, and presents a challenge to existing accounts of repetition effects.

## Experiment 4a

In the interests of comparability with studies of repetition suppression (e.g., Kovács et al., 2012; Larsson & Smith, 2012; Summerfield et al., 2008; 2011), the foregoing studies all used face stimuli. However, faces are “special” in that they have high social significance, activate specific brain structures, and are relatively homogenous – all of which might lead to specific effects of prior exposure and expectation. Experiment 4a therefore examined whether the effects of repetition rate apply for a heterogeneous sample of non-face stimuli.

### Method

**Participants.** Fifty participants (15 male, ages 18-35,  $M = 21.5$ ,  $SD = 3.7$ ) took part.

**Design and Procedure.** A pool of 622 non-face images was taken from those used by Matthews (2011c). They depicted a wide variety of content (e.g., nature scenes, machinery, furniture, plants) subject to the restriction that they did not contain a face. All images measured 343x245 pixels and were presented on a white background. A random sample from this pool was used for each participant.

The block structure and stimulus durations were very similar to previous experiments: participants completed three blocks in the high rep-rate condition followed by three in the low rep-rate condition, or vice-versa. Each block comprised 48 pairs of stimuli, 40 where the second image was shown for 506 ms, 4 where it was shown for 247 ms, and 4 where it was shown for 1000 ms, with 25% of the trials at each duration being of the low frequency type (e.g., repeats in the low rep-rate blocks, non-repeats in the high rep-rate blocks). Participants indicated whether the second image was shown for more or less time than the first, as in Experiment 1. As before, the 247- and 1000-ms stimuli were purely used to monitor attention/comprehension and were not included in the main analysis.

As well as the change in the stimuli, this experiment introduced some procedural modifications. First, each block contained 8 catch trials on which only one image was shown. Participants were instructed not to respond on these trials. Second, the ISI was varied by drawing a random number of frames from a uniform distribution between 247-753 ms. Third, a warning/fixation cross was presented for 247 ms before the first item in each pair, followed by a blank of 353-506 ms. This was to avoid confusion following the trials where only one picture was shown (so that participants clearly knew when the next trial had begun). Finally, a fixed 2 second window was allowed for responses; response collection began at offset of the second image and the next trial began automatically 2

seconds later. (On catch trials, response recording began after offset of the first image.) These changes were introduced in anticipation of subsequent work examining whether repetition rate affects the latency to detect the onset of the second stimulus, described below. The goal was to have a task structure which could be used to investigate the perceived duration of the second image in each pair (the current experiment), and which could then be used in an onset-detection study without changing anything other than the task instructions.

Thus, the sequence of events on each trial was: fixation cross for 247 ms; blank for 247-506 ms; first image for 506 ms; blank ISI for 247-753 ms; second image for 247, 506, or 1000 ms, or blank screen for 506ms (catch trials); blank response window for 2 seconds.

## Results

Six participants were excluded for responding on more than 20% of catch trials, for failing to respond on more than 20% of trials where a second image was shown, or for making erroneous responses on more than 20% of the “easy” trials. (Means for remaining participants: 3.4% responses on catch trials; 3.1% missed responses; 2.4% errors for easy trials.) This left 44 participants, 23 who experienced the low rep-rate blocks first, 21 who completed the high rep-rate blocks first.

The proportions of “longer” responses for the 506-ms test stimuli are plotted in the top left panel of Figure 5. The pattern mirrors the face data: novel stimuli were judged longer than repeats,  $F(1,43) = 15.63, p < .001, \eta_p^2 = .27$ , there was no overall effect of rep-rate,  $F(1,43) = 0.47, p = .495, \eta_p^2 = .01$ , but rep-rate did modulate the effects of repetition  $F(1,43) = 6.88, p = .012, \eta_p^2 = .14$ . As the contrast plot in the top right panel of Figure 5 shows, novel stimuli were judged significantly longer than repeats when repeats were rare but not when they were common. Again as in previous studies, rep-rate primarily affected the judgment of repeated images, which were judged longer in the high rep-rate blocks than in the low rep-rate blocks, whereas repetition frequency did not affect the judgment of novel images.

## Discussion

Experiment 4a found that the pattern obtained with face stimuli generalizes to non-face images, much as the effects of repetition and repetition rate on neural repetition suppression first identified for faces have been generalized to tones and voices (Andics et al., 2013; Todorovic & de Lange, 2012). Taken together, these results point to general (but contradictory) effects for the size of the neural response and behavioural indices of subjective duration, although without recording neural activity during the temporal judgment tasks we must be circumspect about this apparent dissociation.

The next experiment again used non-face images, and asked whether the foregoing effects generalize to a task in which participants attempt to reproduce the target duration by holding down a button for the length of time that the picture was visible. Although many studies assume equivalence between reproduction and other types of temporal judgment, there is mounting evidence for dissociations (e.g., Gil & Droit-Volet, 2011). Most relevantly, Matthews (2011c) found that the effects of stimulus repetition in a reproduction task were the opposite of those in discrimination/estimation tasks.

## Experiment 4b

### Method

**Participants.** Thirty seven participants completed the experiment (11 male, ages 17-49,  $M = 22.6$ ,  $SD = 6.4$ ). One additional participant reported failing to understand the task and was excluded.

**Design and Procedure.** The stimuli were the same non-face images as used in Experiment 4a. The sequence of events on each trial was: the first image for 506 ms, a random ISI of 247-753 ms; the second image for a randomly chosen interval of 506-1000 ms; a 4 second response window, during which participants attempted to hold down the left mouse button for a length of time equal to the duration of the second image. The increased time needed for each trial meant that the number of trials was reduced to avoid fatigue. Thus, participants completed 6 blocks of 36 trials. In the low rep-rate blocks, the two images in each pair were the same for 9 trials and different for 27 trials; in high rep-rate blocks, these values were swapped. Thus, the “rare” trial type occurred on 25% of the trials in a block, as in previous experiments. Alternating participants were assigned to complete three high rep-rate blocks followed by three low rep-rate blocks, or vice-versa. Participants completed six practice trials prior to the main task.

### Results

Trials were excluded if the participant made multiple button presses, started their response before offset of the second picture, made no response, used the wrong mouse button, or responded outside the response window. Three participants were excluded because these errors comprised more than 20% of trials (mean for the remaining participants = 2.1%), leaving a final sample of 34 (17 who completed the low rep-rate blocks first, 17 who completed the high rep-rate blocks first).

The constant error (CE, reproduced duration – target duration) was calculated for each trial and averaged across trials for each condition (see bottom left panel of Figure 5). The constant error was not affected by rep-rate,  $F(1,33) = 0.14$ ,  $p = .708$ ,  $\eta_p^2 = .00$ , or stimulus type,  $F(1,33) = 0.07$ ,  $p = .793$ ,

$\eta_p^2 = .00$ , and there was no interaction,  $F(1,33) = 0.05$ ,  $p = .823$ ,  $\eta_p^2 = .00$ . The same pattern of non-significant findings was obtained when mean reproduced duration (rather than constant error) was used as the DV.

As noted above, the current experiments were highly-powered, and the bottom panels of Figure 5 indicate very little indication of any effects. Nonetheless, one must be cautious about interpreting null results. A reviewer suggested that for this and certain other results that follow, it would be worth calculating Bayes factors (BFs) to quantify the evidence in favour of the null (see e.g., Gallistel, 2009; Kruschke, 2011; Matthews, 2011d; Rouder, Speckman, Sun, Morey, and Iverson, 2009, for discussions of this approach). The fully within-subjects design meant that both the main effects and the interaction could be reduced to paired t-tests. Rouder et al.'s "Bayesian t-test" gave BFs of 5.3 for the main effect of novelty, 5.1 for the main effect of rep-rate, and 5.3 for the interaction, meaning that for all tests the data favoured the null by a factor of about five to one. (This was with the recently-proposed default scaling factor of  $r = 0.707$  --see Morey, Rouder, and Jamil, 2014); using the factor of  $r = 1.0$  originally recommended by Rouder et al., 2009, leads to even stronger evidence for the null.)

## Discussion

This experiment adds to a number of studies suggesting differences between tasks that have previously been used interchangeably. For example, Gil & Droit-Volet (2011) found that angry faces were judged longer than neutral ones in verbal estimation and bisection tasks but not in reproduction or generalization tasks (see also Matthews, 2011c). The reason for these dissociations is not clear. Reproduction tasks can be complicated by motor-timing effects (Droit-Volet, 2010) whereas estimation is a particularly "raw" type of temporal judgment (L.A. Jones, Poliakoff, & Wells 2009; Wearden, 1999). Reproduction may also involve greater working memory demands than simple classification tasks because the observer has to compare the on-going duration of the reproduction against the record of the original experience (although classification tasks might similarly involve continuously comparing the current duration to a previous sample). I will not speculate further about possible reasons for the lack of repetition effects in this study, other than to note that the difference between judgment tasks may help to resolve inconsistencies in the effects of prior exposure reported in the literature (e.g., compare Witherspoon & Allan, 1985, with Ono & Kawahara, 2005).

Experiments 1-4b demonstrate distinct effects of prior exposure and expectation on subjective time: previously-exposed stimuli are judged shorter than novel items when both are equiprobable, but making the repeats more predictable increases their apparent duration relative to novel items.

The remaining studies probe the basis for these effects. Experiments 5 and 6 examine boundary conditions for the effect of prior exposure; Experiments 7a, 7b, 8 and 9 examine the mechanisms underlying the effects of repetition frequency/predictability.

### Experiment 5

One basic question regarding the effect of prior exposure is: how long does the effect last? Studies of the role of “long term” memory on subjective duration have produced mixed results (Matthews, 2011c; Witherspoon & Allan, 1985), but the effect of changes in inter-stimulus interval (ISI) when there are no intervening items between the first and second presentations has not hitherto been addressed. In neural studies, some tasks and measures find repetition suppression that persists for many minutes and over multiple intervening items (see e.g., Grill-Spector et al., 2006), but at least some of the neural correlates of prior exposure are short-lived -- for example, a recent EEG study found that suppression of the N170 response to repeated face stimuli was obliterated as the ISI increased from 400 to 2000 ms (Kuehl, Brandt, Hahn, Dettling, & Neuhaus, 2013). Correspondingly, different mechanisms may underlie short-term and long-lasting suppression effects (e.g., De Baene & Vogels, 2010; Gotts et al., 2012), and these may have differing implications for time perception.

Experiment 5 used the same paradigm as the preliminary study for Experiment 1: participants judged whether the second image was shown for more or less time than the first, and the repetition rate was not varied; half the trials were repeats and half were novel. However, half the trials had the same 306-ms ISI as in Experiment 1 and half had a longer 2000-ms ISI. In addition, and in anticipation of Experiment 6, the stimuli were changed from photographs to abstract patterns.

### Method

**Participants.** Thirty six participants (21 female, ages 19-38,  $M = 24.3$ ,  $SD = 4.9$ ) took part.

**Stimuli.** A set of 75 two-colour icons were constructed by drawing simple, abstract patterns. Each measured 100 x 100 pixels. The stimuli were constructed by arranging sub-sets of these icons into a 3x3 grid. The first, standard stimulus on each trial was constructed by sampling 9 icons without replacement from the set of 75; an example is shown in Figure 6. On repeat trials, the second stimulus was the same as the first; on novel trials, the second image was constructed by sampling without replacement from the 66 icons not used for the first stimulus.

**Design and Procedure.** Participants saw two stimuli and judged whether the second had longer or shorter duration than the first. The trial structure and task were the same as for the preliminary experiment for Experiment 1; the first image was shown for 506 ms and the second for either 247,

506, or 1000 ms. Each block consisted of 48 trials including 8 “easy” trials (4 with the 247-ms comparison duration and 4 with the 1000-ms comparison duration); on half of the trials the standard and comparison stimuli were the same image and on half they were different. Trials order was randomized and participants indicated their responses by pressing the S and L keys of a standard keyboard.

There were six blocks; half had a short ISI (306-ms) and half had a long ISI (2000 ms). Blocks alternated between short- and long-ISIs. Half the participants started with a short-ISI block and half with a long-ISI block.

## Results and Discussion

Five participants were excluded for scoring less than 80% correct on the “easy” trials. The data for the remaining 31 are plotted in Figure 7. A 2x2 within-subjects ANOVA revealed that, overall, novel stimuli were judged longer than repeats,  $F(1, 30) = 17.29, p < .001, \eta_p^2 = .37$ . However, this effect was modulated by the inter-stimulus interval,  $F(1,30) = 24.33, p < .001, \eta_p^2 = .45$ ; the ISI had no main effect,  $F(1, 30) = 0.21, p = .651, \eta_p^2 = .01$ . As can be seen from the contrasts in the right panel of Figure 7, stimulus repetition only affected judgements when the ISI was short; when the interval between the standard and comparison images was 2000 ms, novel and repeated images were judged the same. We return to this finding below.

## Experiment 6

A second potential boundary condition for the effects of prior exposure concerns the need for a lag between the occurrences of the elements that make up the stimulus. In oddball tasks and the two-stimulus paradigm of Experiments 1-5, repeated presentations of the stimuli are separated in time. Yet if the effect of prior exposure is due to novel items being more interesting/informative/arousing than repeats (e.g., New & Scholl, 2009; Seifried & Ulrich, 2010; Ulrich et al., 2006) then we might expect the same effect when we compare a stimulus composed of the same element repeated several times with a stimulus comprising many different features.

## Method

**Participants.** Forty eight participants (13 male, ages 19-51,  $M = 25.1, SD = 7.3$ ) took part.

**Stimuli.** The stimuli were constructed from the set of 75 icons used Experiment 5. On each trial, 10 icons were sampled without replacement. The complex stimulus consisted of 9 of these arranged

in a 3x3 grid; the simple stimulus consisted of repeating the remaining icon in the same 3x3 arrangement.

**Design and Procedure.** The task and durations were as in Experiment 5, with 48 trials per block comprising 40 test trials and 8 “easy” trials, and a fixed ISI of 306 ms. On half of the trials, the first, standard stimulus was simple and the second, comparison stimulus was complex; on the other half the order was reversed. Participants judged whether the second item had long or shorter duration than the first. Comparison duration and stimulus order were fully crossed in each block, and trial order was randomized.

## Results and Discussion

One participant was excluded because he reported that some of the icons had personal significance to him; one was excluded for failing to understand the task; three were excluded for making erroneous responses on more than 20% of the “easy” trials (mean for final sample = 4.2%), leaving a sample of 43 participants.

For each participant, the proportion of trials on which the second image was judged to have longer duration than the first was calculated for both the simple-complex and complex-simple stimulus orders. The mean proportion of trials on which the second image was judged longer than the first was .530 ( $SD = .167$ ) for the order simple-complex and .535 ( $SD = .172$ ) for the order complex-simple. This difference was not significant,  $t(42) = 0.38$ ,  $p = .707$ ,  $BF = 5.7$  (the data favour the null by a factor of 5.7 to 1).

Experiments 5 and 6 suggest boundary conditions for the repetition effect: the repeated presentation of the stimulus elements must be separated in time rather than intra-stimulus (Experiment 6), and the effect is short-lived: when the time between first and second presentations is extended to 2 seconds, novel and pre-exposed stimuli are judged to have the same duration (Experiment 5). We return to these findings in the General Discussion. The remaining experiments explore the mechanisms behind the increased subjective duration for predictable repeats elicited by an increase in repetition frequency.

## Experiment 7

The preceding studies all manipulated stimulus predictability by varying the proportion of repeat/novel trials. Experiment 7 investigated whether alternative manipulations of expectation produce the same effects. The structure of the task was similar to studies of attention in which pre-stimulus cues signal the likely location/modality/features of a forthcoming stimulus. Specifically, all

blocks contained an equal number of repeat and novel trials, but the images on each trial were preceded by cues which either reliably predicted whether the two faces would be identical, or which were uninformative.

In a first experiment, not reported here (full details are available from the author), the cues were shapes presented incidentally prior to the face pair. This study found the usual shortening of apparent duration for repeated items, but this was completely unaffected by the validity of the cue. However, this may have been because of the requirement to learn cue-repetition contingencies over the course of the session (participants were given no explicit information as to their significance or validity). The current experiment therefore used over-learned verbal cues.

## Method

**Participants.** Thirty four participants (9 male, ages 18-50,  $M = 22.0$ ,  $SD = 6.1$ ) took part.

**Design and Procedure.** The trial structure and task were the same as for the preliminary study conducted for Experiment 2a: each block of 48 trials comprised an equal mixture of repeat and novel trials, 40 at the “test” duration (506 ms) and 4 at each of the two “easy” comprehension/attention check durations (247 ms and 1000 ms), and participants classified the duration of the second face in each pair as one of five times.

Participants were told that sometimes the two images shown on each trial would be the same and sometimes they would be different. They were also told that a word would flash on the screen before each pair of photographs, and that “same” meant the two images would be the same, “different” meant that they would be different, whilst “fesa” and “menditref” both meant that the images were equally likely to be the same or different. (The uninformative cues were formed by swapping two letters from each valid cue and then jumbling the letter order.) Informative and uninformative cues were used equally often for each duration in each block, with trial order randomized.

The instructions and practice were generally as in Experiment 2. The practice trials were expanded to include one valid and one invalid cue for both repeat and novel trials at each of the three durations (247, 506, and 1000 ms). In both the practice trials and main task, the use of “fesa” and “menditref” as the invalid cue was randomly determined on each trial. The inclusion of the pre-cue increased the duration of each trial, so the number of blocks was reduced from 6 to 5. (The fact that there is no longer a “rare” stimulus type means that this still gives more trials in each condition than in previous experiments.)

The sequence of events on each trial was: a blank interval for 882-1000 ms; cue for 353 ms; blank interval for 506-753 ms; first face for 506 ms; blank for 306 ms; second face for 247, 506, or 1000 ms; blank until response.

## Results and Discussion

One participant was excluded because their mean judgments for the 1000-ms stimuli were smaller than for the 247-ms stimuli. The mean judgments for each condition are plotted in the left panel of Figure 8. A 2x2 within-subjects ANOVA revealed that novel images were judged longer than repeats,  $F(1,32) = 29.71$ ,  $p < .001$ ,  $\eta_p^2 = .48$ , but there was no main effect of cue validity,  $F(1,32) = 0.02$ ,  $p = .892$ ,  $\eta_p^2 = .00$ , and no validity x repetition interaction,  $F(1,32) = 0.00$ ,  $p = .972$ ,  $\eta_p^2 = .00$ . The Bayes factors for the cue-validity and interaction effects were 5.3 and 5.4 respectively (i.e., the data favour the null by a factor of just over 5:1 in each case). By contrast, the BF for the the main effect of repetition favoured the alternative hypothesis by a factor of more than 3000 to 1.)

In short, duration judgments are sensitive to variations in repetition frequency but manipulating expectations by explicitly signalling the repetition status of forthcoming stimuli does not have the same effect as varying the probability of repetition.

## Sequential Effects

As an additional exploration of the nature of the expectations that underlie the effects of repeat on time perception, I examined trial-by-trial changes in the subjective duration of repeated and novel items. Many studies have shown that attentional processes and perceptual judgments, including temporal judgments, exhibit sequential effects, changing contingent upon recent experience (e.g., Djajas, Bausenhardt, & Ulrich, 2012; Maljkovic & Nakayama, 1994; Matthews & Stewart, 2009; Taatgen & van Rijn, 2011). One possibility is therefore that the effect of making repeats more predictable by increasing the repetition-rate will be paralleled by short-term changes in expectation.

To investigate this, I re-analysed the data from the preliminary and main experiments of Experiment 1 (recall that in the preliminary study the repetition probability was a constant 50% throughout the experiment). Each trial was classified according to whether the comparison stimulus was a repeat or novel, and whether the preceding trial was a repeat-trial or a novel-trial. (Responses to the first trial of each block were excluded.) The mean response proportions are plotted in the top-left panel of Figure 9: the black and white bars indicate responses to novel and repeated items on the current trial, grouped according to whether the previous trial was novel (prev-nov) or a repeat

(prev-rep). As one would expect, there is a main effect of current trial type, with novel stimuli judged longer than repeats,  $F(1,18) = 19.93, p < .001, \eta_p^2 = 0.53$ . However, this is modulated by the previous trial type,  $F(1,18) = 14.57, p = .001, \eta_p^2 = .45$ ; as can be seen in the figure, the repetition effect was smaller when the previous trial was also a repeat. There was no main effect of previous trial type,  $F(1,18) = 0.25, p = .626, \eta_p^2 = .01$ .

The same pattern was found for the main study of Experiment 1. A 2x2x2 within-subjects ANOVA revealed (as in the original analysis) that novel stimuli were judged longer than repeats,  $F(1,64) = 27.73, p < .001, \eta_p^2 = .30$  and that this effect interacted with rep-rate such that the repetition effect was smaller when repeats were common,  $F(1,64) = 5.13, p = .027, \eta_p^2 = .07$ . Importantly, the effect of repetition was also modulated by the condition on the previous trial,  $F(1,64) = 13.27, p = .001, \eta_p^2 = .17$ , and this modulation was independent of rep-rate (i.e., the three-way interaction was not significant),  $F(1,64) = 2.13, p = .149, \eta_p^2 = .03$ . The two-way interaction between current- and previous-trial types is plotted in the bottom left panel of Figure 10. [There was no main effect of rep-rate,  $F(1,64) = 1.63, p = .207, \eta_p^2 = .02$ , no main effect of previous trial type,  $F(1,64) = 0.16, p = .687, \eta_p^2 = .00$ , and no interaction between these two factors,  $F(1,64) = 1.35, p = .250, \eta_p^2 = .02$ .]

Thus, the effect of “local” repetition rate (whether the previous trial was a repeat or not) mirrors the effect of “global” repetition rate (variations in the proportion of repetitions between blocks of trials). The data therefore suggest that observers generate expectations about whether the pair of items on the next trial will be the same or different based upon their most recent experience. I repeated the sequential effects analysis for Experiments 2a and 2b (and the preliminary experiment for these studies), Experiment 3, Experiment 4a, and the main and preliminary studies for Experiment 7. The relative subjective duration of repeated items was increased following repeat trials in 6 of these 7 studies, although the effect was only significant for Experiment 2b.

## Experiment 8

The final two experiments investigate the mechanisms underlying the effects of increasing repetition frequency. One possibility, discussed by Kim and McAuley (2013), is that predictability influences the latency to detect stimulus onset; specifically, these authors found that more deviant/unexpected stimuli were both judged longer and detected more rapidly than predictable

items. Experiment 8 examined onset detection times as a function of prior exposure and repetition rate.

In order to allow the best possible test of whether onset detection underlies the effects of repetition and repetition rate on subjective duration, the trial structure and procedure of this study were identical to Experiment 4a, where the effects on temporal judgment were clearly established. Indeed, Experiment 4a was designed with the possibility of a subsequent onset-detection task in mind. For example, that experiment included catch trials on which no second image was presented; such trials were intended to discourage anticipatory responding in the onset-detection version of the task used here.

## Method

**Participants.** Fifty two participants took part (18 male, ages 18-32,  $M = 21.2$ ,  $SD = 2.5$ ).

**Design and Procedure.** The experiment was identical to Experiment 4a, except for the instructions given to participants. Participants were told that they should press the H key on the keyboard as soon as they saw the second image on each trial. They were warned that responses made before the appearance of the second image would not be recorded and that on some trials there would be only one image, in which case they should not press anything.

The original written instructions referred to seeing “pairs of images” on each trial. Feedback from two of the first eight participants indicated that they had not understood the task and had only been responding when the two images were the same (a “pair”). The written instructions were therefore modified for subsequent participants to eliminate all mention of “pairs” (e.g., replacing “Your task is to press the H key as soon as the second picture in the pair appears on the screen” with “Your task is to press the H key as soon as the second picture appears on the screen. It doesn’t matter what the picture is – just press H as soon as you see it”).

## Results and Discussion

Trials with RTs less than 100ms or more than 1000ms were assumed to represent anticipatory responses/attentional lapses and were excluded. In addition to the two participants who self-reported misunderstanding the task, nine participants were excluded for responding on more than 20% of catch trials or having missing data for more than 20% of the non-catch trials (means for remaining participants 3.7% and 2.7%, respectively), leaving a sample of 41 participants, 20 who completed the low rep-rate blocks before the high rep-rate blocks and 21 with the reverse order. By analogy with the temporal judgment task, analysis was limited to trials where the second image had a duration 506 ms (collapsing across all durations produced the same results).

The mean response latencies for each condition are plotted in the top left panel of Figure 10. A 2x2 within-subjects ANOVA showed no overall effect of stimulus repetition,  $F(1,40) = 1.04, p = .314, \eta_p^2 = .03$ , no overall effect of repetition rate,  $F(1,40) = 0.51, p = .479, \eta_p^2 = .01$ , and no interaction,  $F(1,40) = 0.06, p = .807, \eta_p^2 = .002$ . Bayes factors led to the same conclusions, favouring the null for all three tests ( $BF_{\text{repetition}}=3.7, BF_{\text{rep-rate}}=4.7, BF_{\text{interaction}}=5.8$ ).

Experiment 8 therefore found no evidence that repetition or repetition rate affected the time taken to detect the onset of the second image on each trial. This runs contrary to the findings of Kim and McAuley (2013), although there are many differences between the two studies, including (a) their use of auditory stimuli, (b) the fact that each trial of the current experiments used unique images whereas Kim and McAuley presented the same stimuli throughout the session, (c) the inclusion of catch trials in the current experiments, and (d) Kim and McAuley's use of an oddball paradigm, where the position of the to-be-detected stimulus in the sequence varied from trial to trial, whereas the current experiment varied the time between the offset of the first stimulus and the onset of the to-be-detected image. Although we cannot rule out any effect of repetition/repetition rate on onset detection, the available data suggest that this is not a major contributor to the effects found in Experiments 1, 2a, 2b, 3, and 4a.

## Experiment 9

Experiment 9 asks whether repetition rate influences “higher-level” stimulus processing (i.e., processing that occurs after simple onset detection) by measuring its effect on the time taken to classify the test images as male or female. As before, apart from the instructions, the experiment was identical to a previous study (Experiment 2b this time) which demonstrated the repetition and rep-rate effects on time perception.

### Method

**Participants.** Twenty seven participants took part (8 male, ages 17-31,  $M = 21.1, SD = 3.1$ ).

**Design and Procedure.** The experiment was identical to Experiment 2b, except that the participants' task was to identify the gender of the second face in each pair as quickly as possible. The sequence of events on each trial was therefore: blank interval for 882-1118 ms; first face for 506 ms; blank ISI for 306 ms; second face for 247, 506, or 1000 ms; blank interval until response. Response recording began as soon as the second face appeared on the screen. If a response was made while the second image was still visible, the next trial began as soon as presentation was complete.

Participants indicated the gender of the second face by pressing the “0” and “1” keys on the keyboard (assignment of keys to gender was alternated across participants). Participants were told to respond as fast as possible whilst maintaining accuracy.

The pool of 622 faces comprised 290 males and 332 females. However, the actual gender of the faces shown on a given trial was not an important factor: the only issue is whether the effect of seeing exactly the same face (be it male or female) before the target face affects the time taken to classify its gender, and whether this effect is modulated by the frequency with which such repetitions occur.

## Results and Discussion

Response times less than 150 ms were judged anticipatory and excluded (this pre-set criterion was longer than in Experiment 8 on the assumption that the minimum latency for semantic classification will be longer than for onset detection; in practice, the precise choice of criteria makes little difference.) Three participants were excluded for making erroneous/missing/anticipatory responses on more than 20% of trials, giving 24 useable participants (13 who experienced the low rep-rate blocks before the high rep-rate blocks, 11 with the reverse order). In the interests of direct comparability with the temporal judgment data of Experiment 2b, we focussed on the responses to the target stimuli (i.e., those with 506-ms durations), but the pattern of significant effects was identical collapsing across duration (i.e., when the 247- and 1000-ms “easy” items were included).

The error rates were very similar in all conditions: in the low rep-rate blocks,  $M_{\text{novel}} = 5.3\%$  ( $SD = 3.0\%$ ),  $M_{\text{rep}} = 5.0\%$  ( $SD = 4.0\%$ ); in the high rep-rate blocks,  $M_{\text{novel}} = 5.6\%$  ( $SD = 5.0\%$ ),  $M_{\text{rep}} = 4.0\%$  ( $SD = 29\%$ ). A 2x2 within-subjects ANOVA confirmed that there was no overall difference in the error rates for repeat and novel trials,  $F(1,23) = 1.22$ ,  $p = .281$ ,  $\eta_p^2 = .05$ , no main effect of rep-rate,  $F(1,23) = 0.27$ ,  $p = .606$ ,  $\eta_p^2 = .01$ , and no interaction,  $F(1,23) = 1.91$ ,  $p = .180$ ,  $\eta_p^2 = .08^1$ .

The main focus is on mean correct RTs, which are plotted in the middle left panel of Figure 10. Overall, responses were faster when the second image was a repeat than when it was novel,  $F(1,23) = 14.64$ ,  $p = .001$ ,  $\eta_p^2 = .39$ . There was no main effect of rep-rate,  $F(1,23) = 1.18$ ,  $p = .289$ ,  $\eta_p^2 = .05$ , but rep-rate did modulate the effects of stimulus repetition,  $F(1,23) = 14.63$ ,  $p = .001$ ,  $\eta_p^2 = .39$ . As can be seen from the 95% confidence intervals around the contrasts plotted in the middle right

---

<sup>1</sup> ANOVA may not be appropriate for proportion data with such low values. Fitting a generalized linear model with a logit link function using the lme4 package of R (Bates, Maechler, Bolker, & Walker, 2014) led to the same conclusions (95% profile confidence intervals for all three effects spanned zero). Perhaps more importantly, the absolute difference between the lowest and highest error rates is only 1.6%, so any effect is very small in absolute terms.)

panel of Figure 9, responses were faster for repeats when repetitions were common (high rep-rate blocks) but not when they were rare (low rep-rate blocks). This difference was driven by a significant shortening of reaction times to repeated stimuli in the high rep-rate blocks relative to the low rep-rate blocks; the responses to novel stimuli were not significantly affected by rep-rate.

The foregoing leaves open the locus of the RT improvement for repeated items. In particular, when repetitions are common the gender of the first face is a valid cue to the response that will be required to the target, so the faster RTs may be due to response preparation rather than a change in the efficiency with which the target is processed. To explore this possibility, I divided the non-repeat trials into those where the target was the same gender as the standard and those where the gender was different. If repetition probability shortens RTs for repeated stimuli purely via response priming, the effect should generalize to trials where the same response is required even if the identity of the face is different.

The mean RTs for correct responses are plotted in the bottom left panel of Figure 10. A 2 x 3 ANOVA with rep-rate (low vs high) and repetition condition (different gender, same gender but different face, identical face) as within-subject factors revealed a main effect of repetition condition,  $F(1.57, 36.03) = 11.64, p < .001, \eta_p^2 = .34$  which was affected by the repetition rate,  $F(1.60, 36.84) = 8.52, p = .002, \eta_p^2 = .27$ . There was no overall effect of rep-rate,  $F(1, 23) = 0.32, p = .580, \eta_p^2 = .01$ . (The same patterns were found when the analyses were conducted using trials of all stimulus durations rather than just the target durations.)

As can be seen from the contrast plots in the bottom right panel of Figure 10, increasing the repetition rate accelerated responses to identical faces but had no significant effect on responses to different faces, whether of the same or a different gender. This suggests that repetition rate affected the speed with which perceptual information was extracted from the repeated image; if the faster responses to repeated images were purely a response-priming effect, it would be expected to generalize to other stimuli that require the same motor output (although there might be a response-priming effect which is cancelled as soon as any difference between the second and first stimuli is detected).

In short, the response-time data parallel the repetition suppression effects found in neuroimaging studies: when repeated stimuli are common, repeats evoke smaller neural responses and faster reaction times than novel stimuli; when repeats are rare, these effects diminish or disappear (compare the middle panel of Figure 10 with the bottom panels of Figure 1). Together, these data point to more efficient processing of repeated stimuli when those stimuli are more predictable.

## General Discussion

Empirical and theoretical treatments of the repetition effect on time perception have emphasized the idea that repeated stimuli are more expected than novel or rare items, and that this expectation compresses the subjective duration of repeats (e.g., Pariyadath & Eagleman, 2007; Matthews, 2011c; New & Scholl, 2009; Schindel et al., 2011; Tse et al., 2004; Seifried & Ulrich, 2010; Ulrich et al., 2006). Under this view, making repetitions more predictable by increasing the proportion of stimulus pairs for which the second item is a repeat of the first ought to exacerbate the subjective shortening of repeated stimuli. The present experiments found the opposite: increasing the repetition rate reduced, eliminated, and even reversed the usual shortening of subjective duration for repeated images. This held for face- and non-face photographs, across a range of durations, and occurred both when the second image in each pair was explicitly compared with the first and when the target image was simply judged on a categorical scale. Sequential effects analysis suggests that the effect is the result of trial-by-trial updating of expectations about repetition probabilities. The effect is primarily driven by a relative lengthening of repeated stimuli when repeats are common, and does not seem to be driven by changes in onset detection latency.

These findings suggest that immediate repetition (that is, very recent prior exposure) and higher-order expectations about stimulus identity exert distinct effects on subjective time. On the one hand, recent exposure elicits a robust shortening of perceived duration relative to newer items. On the other, when repetition of the current item is highly predictable the subjective duration of its second occurrence is lengthened. That is, whereas previous accounts have posited that repeated stimuli have shorter apparent duration because they are expected, the current data suggest a more complex view: immediate repetition does shorten apparent duration when repetitions comprise 25% or 50% of the trials (and are therefore not especially expected), but making repetitions predictable increases the relative subjective duration of the repeated items.

### **Prior exposure and repetition-expectation are functionally distinct**

Before relating the current data to theories of timing, it is worth considering some general implications. Most discussions of repetition effects contrast two possibilities: such effects may be a low-level consequence of prior exposure, independent of expectations about forthcoming stimuli; or they may reflect implicit expectations about future experiences, in which case they will be strengthened when repeats become more common. There is evidence for both possibilities, but over-arching theories of cognition and neuroscience have emphasized the expectation-based

account (e.g., J.R. Anderson & Milson, 1989; Friston, 2005), and studies of neural repetition suppression have supported this view (e.g., Mayrhauser et al., 2014; Summerfield et al., 2008).

The current data are a reminder that there is a third possibility: first-order repetition and second-order repetition frequency may have opposing effects. Finding this pattern does not, of course, negate the “hierarchical prediction machine” view of cognition (Clark, 2013), but it does provide an important qualification: one cannot assume functional equivalence between the effects of repetition and the effects of making repetition more predictable. This is important for *any* expectation-based view of repetition effects, irrespective of whether one posits a mechanism based on attention, arousal, size-of-neural-response, or something else. Moreover, this qualification poses a theoretical challenge because it is hard to see how opposing effects of immediate repetition and second-order repetition probability make optimal use of prior information to predict future events. What kind of environmental structure or past experience might lead to such a dissociation? Similarly, the opposing perceptual consequences of first-order repetition and second-order repetition probability mean that, if the predictive-coding view of brain organization is correct and the cortex does comprise a hierarchical series of prediction- and error-units, the functional consequences of error at early and later stages can nonetheless be quite distinct.

### **Subjective time, expectation, and coding efficiency**

Turning to the specific topic of repetition effects in time perception, researchers have attributed the repetition effect to repeated stimuli being more expected and thus receiving less attention (Tse et al., 2004), taking longer to detect (Kim & McAuley, 2013), being less arousing (New & Scholl, 2009; Ulrich et al., 2006), or eliciting a smaller neural response (Matthews, 2011c; Pariyadath & Egleman, 2007, 2012; Schindel et al., 2011). These (not necessarily exclusive) possibilities share the idea that repetition effects are a manifestation of implicit expectations. As such, while attention, preferential detection, and arousal may all play a role, these existing accounts cannot capture the pattern found here.

The present findings are particularly relevant to the idea that the subjective duration of a stimulus is positively related to the magnitude of the neural response that it evokes (Egleman & Pariyadath, 2009). The effect of repetition has been central to this argument because of the robust repetition suppression found in studies of evoked neural responses, and proponents of this view have emphasized the predictive coding conception of repetition suppression rather than low-level adaptation (Matthews, 2011c; Pariyadath & Egleman, 2007, 2008, 2012; Schindel et al., 2011). That is, rare or novel stimuli are perceived to last longer because they evoke a larger prediction-error signal than “expected”, repeated items.

The current data do not, of course, directly challenge the idea that the brain is organized as a hierarchy of processing stages which successively “explain away” prediction error – especially given that there are multiple ways in which this predictive coding might be implemented (e.g., Friston, 2009; Spratling, 2008). However, they do cast doubt on the idea of a simple correspondence between the overall evoked response magnitude and subjective time (see also Kononowicz and van Rijn, 2014). Neuroimaging has predominantly found a larger difference between repeated and non-repeated stimuli when repeats are common, consistent with greater suppression for repeats when they are more predictable (e.g., Andics et al., 2013) or, in rare cases, have found repetition suppression that is unaffected by repetition probability (Kaliukhovic & Vogels, 2011; Kovács et al., 2013). By contrast, I found a smaller difference between novel and repeated items as the repeats became more frequent. The difference between the neural and behavioural data is readily seen by comparing Figures 1 and 3.

This dissociation cannot be confirmed without simultaneous recording of neural activity and temporal judgments. Nonetheless, the face stimuli used here are from databases used in the neuroimaging work, and the trial structure was similar to those studies. Moreover, the neural effects have generalized robustly: the effect is the same for faces, tones, and voices (e.g., Andics et al., 2013; Summerfield et al., 2008; Todorovic & de Lange, 2012) and, for face stimuli, is position invariant (Kovács et al., 2012); it has been replicated in studies using fMRI, EEG, and MEG, and across different brain regions and tasks (Larsson & Smith, 2012; Summerfield et al., 2011; Todorovic et al., 2011). One obvious difference between the current experiments and the neuroimaging studies is that the former required temporal judgments; however, the neuroimaging results have generalized across tasks including monitoring face inversion, size changes, rotation, tone pitch and voice volume-changes (Andics et al., 2013; Summerfield et al., 2008; Summerfield et al., 2011; Todorovic & De Lange, 2012); the time-perception effect similarly generalized across stimuli and tasks. This gives reasonable confidence that the difference is not due to a specific task demand or methodological quirk, but it will obviously be important to measure evoked responses in the duration-judgment task to test the dissociation suggested by the existing data.

Even if one rejects a direct link between subjective duration and the overall magnitude of the evoked response, timing must ultimately be grounded in neural activity, and close inspection of the neural data reveals some consistency with the dissociable effects of immediate repetition and expectation on time perception. Kaliukhovic and Vogels (2011) found repetition suppression in macaque inferior temporal cortex to be unaffected by repetition rate; such expectation-independent suppression may be relevant to the current findings (see below). Similarly, human MEG recording by Todorovic and de Lange (2012) recently found that repeated auditory stimuli evoked smaller

responses than non-repeats early in processing (40-60 ms after onset) whereas expected stimuli evoked smaller responses than unexpected ones later in processing (100-200 ms post-onset), which the authors take to indicate a hierarchy of predictive coding, with early stages sensitive to local transition probabilities (i.e., repeat vs novel stimulus) and higher-level regularities coded later in the processing pathway (Friston, 2005; Kiebel, Daunizeau, & Friston, 2008; Wacongne et al., 2011). Thus, while subjective time may not be a simple consequence of the overall magnitude of the evoked response, it might be possible to establish correspondence between time perception and specific components of a predictive-coding hierarchy.

### **Time perception as a function of the interplay between bottom-up and top-down processes**

Given that the effects of repetition and repetition-rate prove challenging for extant accounts, how are they to be explained? Without committing to specific neural structures or implementations, perception is often conceptualized as involving a series of stages leading to progressively more integrated representations of the stimulus, with early stages representing basic features and later stages encoding higher-level conjunctions and, ultimately, object representations that support identification and semantic classification. These higher-level representations depend on an interaction between bottom-up sensory information and top-down modulation such as the attention-driven enhancement of relevant representations.

One straightforward possibility is that subjective duration corresponds to the strength of the percept that results from this sequence of processing stages. “Strength” is used here in a general way, without affirming a specific neural implementation (e.g., the amplitude or rate of neural responses, or changes in the connectivity of neural networks). Rather, I am suggesting a broad information-processing framework in which subjective time depends on the transmission of sensory information to perceptual representations of the kind that support stimulus identification and classification. Correspondingly, manipulations which improve the accuracy/rate of perceptual decision-making will lengthen apparent duration.

Within this framework, apparent duration will be modulated both by changes in the effective input signal and by top-down enhancement of relevant representations. The basic, compressive effect of stimulus repetition on apparent duration would then be an instance of the former, whereas the expansive effect of increasing the predictability of repeated stimuli would be a product of the latter. That is, very recent exposure to a stimulus will weaken the bottom-up signal strength and shorten apparent duration, but to the extent that a repeated item is expected there will be an opposing top-down enhancement of processing for the anticipated features, strengthening the percept and increasing both the efficiency of perceptual decision-making and the subjective duration

of the stimulus. Under this account, increasing the repetition rate will mean that recently-encountered items are more expected, enhancing their perceptual processing and expanding their apparent duration. Evidence for such enhanced perceptual processing was found in Experiment 9, where gender categorization for repeated faces was faster when those repeats were more predictable; evidence for a corresponding increase in subjective duration was found in Experiments 1, 2, 3, and 4a.

Consistent with the bottom-up component of this framework, previous work has shown that subjective duration is lengthened when input is amplified by increases in stimulus magnitude (size, number, intensity, or contrast; e.g., Matthews et al., 2011; Xuan, Zhang, He, & Chen., 2007) – that is, by increases in the effective size/strength of the input signal. In contrast, adapting the sensory system to a particular stimulus feature weakens the effective input, suppressing the corresponding percept and shortening the duration of subsequent occurrences of that feature in the same location (e.g., Bruno et al., 2013; Burr et al., 2007). The locus of this modulation is debated, but the fact that it is spatiotopic confirms that it is not operating at the highest level of stimulus representation.

The repetition effect studied in the present work was found in Experiments 5 and 6 to be short-lived (dissipating after a 2-second ISI) and spatially-specific (repeating elements within a stimulus had no effect, whereas repeating them between successively-presented stimuli led to a contraction of apparent duration). These properties fit with the idea that repetition shortens subjective duration via adaptation at a relatively early stage in processing; indeed, the short time-course may suggest a basic biochemical process, such as fatigue/vesicle depletion among the relevant feature-sensitive neurons. Of course, the current experiments used presentations shorter than the prolonged exposures typical of adaptation studies, but this does not negate the idea of a reduction in effective input strength due to transient, perhaps spatiotopic diminished sensitivity at a relatively early stage of processing (but see Schindel et al., 2011, for evidence that the effect is not due to the very earliest stages of encoding, a conclusion further suggested by the absence of an onset-detection effect in the present Experiment 8).

Turning to top-down modulation, prior studies have found that increasing a stimulus' predictability (for example, by signalling its likely location or reducing uncertainty about when it will occur) improves information extraction (e.g., Bausenhardt, Rolke, & Ulrich, 2007; Carrasco & McElree, 2001; Yeshurun & Carrasco, 1998). Such signal-enhancement has been attributed to back-projections from higher areas boosting the gain of relevant lower-level neurons (e.g., Reynolds, Pasternak, & Desimone, 2000; see Maunsell & Treue, 2006, for a review). Indeed, although predictive-coding theories emphasize inhibition of earlier areas by later ones, most back-projections are excitatory, amplifying responses for relevant features and locations (see Spratling, 2008, for a

reconciliation of this difference). Within the framework outlined above, such increases in gain should expand subjective time, and previous studies of time perception support the idea that these attention-based boosts to the strength of the percept correspond to increased apparent duration. Mattes and Ulrich (1998) cued the modality of forthcoming stimuli and found that their apparent duration lengthened as modality became more predictable. Similarly, Enns et al. (1999) found that the subjective duration of brief flashes was longer when they occurred in locations to which attention had been directed by arrow cues; endogenous cues (such as a bar flashed at the target location) produce the same effect (e.g., Seifried & Ulrich, 2011; Yeshurun & Marom, 2008), as does reducing uncertainty about *when* an item will be presented (e.g., Grondin & Rammsayer, 2003).

Thus, although theorists have attributed the repetition effect in time perception to repeated stimuli being more expected, studies of attention suggest that predictability actually prolongs apparent duration. From this perspective, making the identity of repeated stimuli more predictable by increasing the repetition rate will lengthen the apparent duration of those stimuli because higher-level expectations will amplify relevant earlier-stage representations. Moreover, this increase in gain will produce superior high-level representations of the stimuli, supporting better perceptual/semantic decision-making. Both the prolonged apparent duration and the improved semantic classification for predictable repeats were found in the current experiments.

In this framework, increasing the repetition rate will boost the gain for recently-encountered features and reduce the perceptual strength of unexpected, novel stimuli. Given the large number of features making up a given image, the enhancement will be for a relatively small portion of the feature space while the decrease will be more diffuse. Correspondingly, we would expect a large increase for the repeated items and a smaller reduction for any given novel stimulus. The present research has focused on the difference between judgments of novel and repeated stimuli rather than on whether changes in this difference are driven by the responses to novel or repeated items. However, the contrast plots suggest that the reduced repetition effect is primarily due to increases in the subjective duration of repeats, although there seems to be some reduction in the apparent duration of novel items, too. Interpreting this pattern is problematic because the relativity of judgment means that responses are a function of the difference between percepts, not a direct window on their “absolute” subjective magnitude (e.g., Stewart, Brown, & Chater, 2005; Stewart & Matthews, 2009). For example, even if repetition frequency only affected the perceived duration of repeated items, it may still change the judgments for both repeated and novel images. Nonetheless, the large effect of repetition frequency for repeated items and the smaller change for novel ones is consistent with the framework outlined here.

## Possible implementations

The foregoing provides a general framework. I have outlined possible neural bases for the component processes, but the core idea that subjective time is a positive function of the strength of perceptual representation, which in turn depends on an interplay between bottom-up input-strength and top-down gain control, does not assume a particular neural mechanism. As such, this information-processing approach does not predict a straightforward relation between subjective duration and the overall size of the response evoked by the stimulus (cf. the coding efficiency view described above); rather, it predicts that factors which improve perceptual processing (i.e., those which improve the accuracy and rate of perceptual decision-making) will prolong apparent duration. Nonetheless, it is worth considering how this framework might be related to current mechanistic models of timing.

Many accounts assume that the raw material of temporal perception is the pulses or counts emitted by an internal pacemaker, whose accumulation begins and ends with stimulus onset/offset and whose total number provides the measure of elapsed time (e.g., Gibbon et al., 1984; Treisman, 1963; Wearden, 1992; Zakay & Block, 1997; for a general treatment see Rammsayer and Ulrich, 2001). Some theories identify these pulses with neural firing, but they are often an abstract construct. Crucially, despite the dedicated nature of the putative pacemaker, its rate has been taken to be influenced by a panoply of non-temporal variables, including intensity, modality, motion, emotionality and, as we have discussed, novelty (Droit-Volet & Gil, 2009; Matthews, 2011a, b; Matthews et al., 2011; New and Scholl, 2009; Ulrich et al., 2006; Wearden, Edwards, Fakhri, & Percival, 1998). This lability is a strange feature for a dedicated timing device, and no centralized pulse-emitter has yet been found.

One straightforward possibility is that the pulses of the pacemaker correspond to the activity associated with high-level stimulus representations, those at the end of the sequence of perceptual processing stages. This might entail counting neural spikes, but metrics based on other changes in cortical networks might serve the same function (Mauk and Buonomano, 2004). In any case, the idea that the “pacemaker-pulses” correspond to the activity associated with the formation of high-level stimulus representations may explain why so many non-temporal features affect the effective rate of the putative pacemaker.

A related framework attributes timing to cortical oscillators whose periods are synchronized at stimulus onset; thereafter, the subset of oscillators with coincident activity provides a measure of elapsed time. The striatal beat-frequency model provides one version of this idea, attributing different components of the model (which can be mapped on to those of the pacemaker-accumulator framework) to specific neural structures (Buhusi and Meck, 2005; Matell and Meck,

2004; Merchant et al., 2013). Importantly, recent work has emphasized the links between timing and high-level stimulus representations: the neuroanatomical structures underlying timing largely overlap with those of working memory, and the same neural representation (namely, cortical oscillations) may encode information about both stimulus identity and stimulus duration (Gu, van Rijn, & Meck, in press; Lustig, Matell, & Meck, 2005; van Rijn, Gu, and Meck, in press). By linking timing to high-level representations of stimulus identity, and by emphasizing the links between peripheral and central processes (Merchant et al., 2008, 2013), the beat-frequency model may provide a framework for incorporating the information processing account outlined here.

### **Conclusions and future directions**

The present research suggests opposing effects on subjective time of prior exposure and higher-order expectations, with the former producing a robust contraction and the latter producing a relative expansion for repeated items. This general point is important for cognitive and neuroscientific theories that posit unitary effects of first and second order expectations. The data are problematic for extant accounts of repetition effects on timing, but can be accommodated within a framework in which subjective duration is positively related to the strength of perceptual representations of the type that support stimulus identification and classification, and which therefore depend on low-level changes in the effective input signal and the amplification of this signal by top-down expectations. These findings suggest a number of directions for future work.

First, it will be important to see whether the opposing effects of repetition and repetition-expectation found here arise for other perceptual judgments. Relatedly, it will be interesting to consider adaptive explanations for this pattern, based on environmental contingencies or pre-experimental experiences, such that it could be incorporated within the increasingly prevalent view of the mind as a Bayesian optimizer.

Second, the apparently divergent effects of repetition probability on time perception and on neural response magnitude urges an experiment which manipulates repetition probability whilst recording neural activity trial-by-trial and examines the relation between these responses and subjective duration.

Third, given the importance of discrimination accuracy to theories of timing (e.g., Grondin, 2012; Matthews & Grondin, 2012; Rammsayer & Ulrich, 2001), it will be important to establish how repetition and repetition probability affect this measure. The current findings generalized across image types, meaning that it should be possible to harvest sufficient stimuli to permit estimation of the psychometric function.

Fourth, it will be instructive to employ non-repeated stimuli that are nonetheless perfectly predictable. In the present work, non-repeats were always completely new and unpredictable, but one could have contingencies such that (for example) stimulus A is always followed by B whereas C is equally likely to be followed by D or E, further illuminating the contributions of repetition and expectation. Likewise, many studies have employed an oddball paradigm where the same standards and oddballs are used across trials (that is, oddballs are rare rather than strictly novel). Varying the prevalence of particular standards and oddballs throughout the experiment could disambiguate the contributions of repetition, frequency, and genuine novelty.

Fifth, the roles of intra-stimulus repetition and complexity demand further scrutiny. The present Experiment 6 suggests that a “boring” stimulus comprising repeated elements is judged no differently from an “interesting”, heterogeneous item, but other work has found that complexity does affect the apparent duration of tone and light sequences (e.g., Aubry, Guillaume, Morigato, Bergeret, & Celsis, 2008; Matthews, 2013; Schiffman & Bobko, 1974) and the effects of complexity may depend on whether the participant has to process the non-temporal structure of the stimulus (e.g., Varakin, Klemes, & Porter, 2013).

Sixth, it will be important to clarify the types of expectations which modulate the repetition effect. Variations in repetition rate produced functionally-important shifts in implicit predictions based on trial-by-trial updating of expectancies, but there was no effect of verbally signalling whether the next pair of items would be the same or different. This may suggest a difference between “implicit” perceptual predictions, which prolong subjective duration, and the effects of explicit cues, which may require higher-level intentional orienting or perceptual anticipation and which do not automatically entail an expansion of apparent time.

Finally, it would be useful to investigate the processing levels at which repetition can influence subjective time. Prior work has focused on the repetition of perceptual features, but studies of priming routinely find that semantic relations between the first and second stimulus are sufficient to moderate processing (e.g., Neely, 1991); is there a similar semantic-repetition effect on time perception?

## **Acknowledgements**

I am grateful to Mair Thomas and Warren Meck for helpful discussion and comments on earlier versions of this work.

## References

- Allman, M. J., Teki, S., Griffiths, T.D., & Meck, W.H. (2013). Properties of the internal clock: First- and second-order principles of subjective time. *Annual Review of Psychology, 65*, 743-771. doi: 10.1146/annurev-psych-010213-115117
- Anderson, J.R., & Milson, R. (1989). Human memory: An adaptive perspective. *Psychological Review, 96*(4), 703-719.
- Anderson, J. R., & Schooler, L. J. (1991). Reflections of the environment in memory. *Psychological Science, 2*(6), 396-408. doi: 10.1111/j.1467-9280.1991.tb00174.x
- Anderson, R.B., Tweney, R.D., Rivardo, M., & Duncan, S. (1997). Need probability affects retention: A direct demonstration. *Memory & Cognition, 25*(6), 867-872.
- Andics, A., Gál, V., Vicsi, K., Rudas, G., & Vidnyánszky, Z. (2013). fMRI repetition suppression for voices is modulated by stimulus expectations. *Neuroimage, 69*, 277-283. doi: 10.1016/j.neuroimage.2012.12.033
- Aubry, F., Guillaume, N., Morigato, G., Bergeret, L., Celsis, P. (2008). Stimulus complexity and prospective timing: Clues for a parallel process model of time perception. *Acta Psychologica, 128*, 63-74. doi: 10.1016/j.actpsy.2007.09.011
- Bar, M. (2009). Predictions: a universal principle in the operation of the human brain. *Philosophical Transactions of the Royal Society B: Biological Sciences, 364*, 1181-1182. doi:10.1098/rstb.2008.0321
- Bates, D.M., Maechler, M., Bolker, B., & Walker, S. (2014). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1-5.
- Bausenhart, K. M., Rolke, B., & Ulrich, R. (2007). Knowing when to hear aids what to hear. *Quarterly Journal of Experimental Psychology, 60*(12), 1610-1615. doi: 10.1080/17470210701536419
- Birngruber, T., Schröter, H., & Ulrich, R. (2014). Duration perception of visual and auditory oddball stimuli: Does judgment task modulate the temporal oddball effect? *Attention, Perception, & Psychophysics, 76*, 814-828. doi: 10.3758/s13414-013-0602-2
- Block, R.A., Hancock, P.A., & Zakay, D. (2010). How cognitive load affects duration judgments: A meta-analytic review. *Acta Psychologica, 134*, 330-343. doi: 10.1016/j.actpsy.2010.03.006
- Bodner, G.E., & Dypvik, A.T. (2005). Masked priming of number judgments depends on prime validity and task. *Memory & Cognition, 33*(1), 29-47.
- Bodner, G.E., & Masson, M.E.J. (2001). Prime Validity Affects Masked Repetition Priming: Evidence for an Episodic Resource Account of Priming. *Journal of Memory and Language, 45*(4), 616-647. doi: 10.1006/jmla.2001.2791

- Bodner, G.E., & Masson, M.E.J. (2004). Beyond binary judgments: Prime validity modulates masked repetition priming in the naming task. *Memory & Cognition*, *32*(1), 1-11.
- Bruno, A., Ng, E., & Johnston, A. (2013). Motion-direction specificity for adaptation-induced duration compression depends on temporal frequency. *Journal of Vision*, *13*(12), 1-11. doi:10.1167/13.12.19.
- Buhusi, C.V., & Meck, W.H. (2005). What makes us tick? Functional and neural mechanisms of interval timing. *Nature Reviews Neuroscience*, *6*, 755-765. doi: 10.1038/nrn1764
- Buhusi, C.V., & Meck, W.H. (2009). Relativity theory and time perception: Single or multiple clocks? *PLOS ONE*, *4*(7), Article e6268, 1-6. doi: 10.1371/journal.pone.0006268
- Buonomano, D. V., & Maass, W. (2009). State-dependent computations: spatiotemporal processing in cortical networks. *Nature Reviews Neuroscience*, *10*(2), 113-125. doi: 10.1038/Nrn2558
- Burr, D.C., Cicchini, G.M., Arrighi, R., & Morrone, M.C. (2011). Spatiotopic selectivity of adaptation-based compression of event duration. *Journal of Vision*, *11*(2), 1-9. doi: 10.1167/11.2.21
- Burton, A. M., White, D., & McNeill, A. (2010). The Glasgow face matching test. *Behavior Research Methods*, *42*(1), 286-291. doi: 10.3758/Brm.42.1.286
- Casini, L., & Macar, F. (1997). Effects of attention manipulation on judgments of duration and of intensity in the visual modality. *Memory & Cognition*, *25*(6), 812-818. doi: 10.3758/Bf03211325
- Chater, N., & Manning, C.D. (2006). Probabilistic models of language processing and acquisition. *Trends in Cognitive Sciences*, *10*(7). 335-344. doi:10.1016/j.tics.2006.05.006
- Clark, A. (2013). Whatever next? Predictive brains, situation agents, and the future of cognitive science. *Behavioral and Brain Sciences*, *36*, 181-253. doi:10.1017/S0140525X12000477
- Creelman, C.D. (1962). Human discrimination of auditory duration. *Journal of the Acoustical Society of America*, *34*(5), 582-593.
- Curran, W., & Benton, C.P. (2012). The many directions of time. *Cognition*, *122*, 252-257. doi: 10.1016/j.cognition.2011.10.016
- De Baene, W., & Vogels, R. (2010). Effects of adaptation on the stimulus selectivity of macaque inferior temporal spiking activity and local field potentials. *Cerebral Cortex*, *20*(9), 2145-2165. doi: 10.1093/cercor/bhp277
- Desimone, R. (1996). Neural mechanisms for visual memory and their role in attention. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(24), 13494-13499. doi: 10.1073/pnas.93.24.13494

- Droit-Volet, S. (2010). Stop using time reproduction tasks in a comparative perspective without further analyses of the role of the motor response: The example of children. *European Journal of Cognitive Psychology*, 22(1), 130-148. doi: 10.1080/09541440902738900
- Droit-Volet, S., & Gil, S. (2009). The time-emotion paradox. *Philosophical Transactions of the Royal Society B-Biological Sciences*, 364(1525), 1943-1953. doi: DOI 10.1098/rstb.2009.0013
- Durso, F. T., & Johnson, M. K. (1979). Facilitation in naming and categorizing repeated pictures and words. *Journal of Experimental Psychology: Human Learning and Memory*, 5(5), 449-459. doi: 10.1037/0278-7393.5.5.449
- Dyjas, O., Bausenhardt, K.M., & Ulrich, R. (2012). Trial-by-trial updating of an internal reference in discrimination tasks: Evidence from effects of stimulus order and trial sequence. *Attention, Perception, & Psychophysics*, 74, 1819-1841. doi: 10.3758/s13414-012-0362-4
- Eagleman, D. M. (2008). Human time perception and its illusions. *Current Opinion in Neurobiology*, 18(2), 131-136. doi: 10.1016/j.conb.2008.06.002
- Eagleman, D. M., & Pariyadath, V. (2009). Is subjective duration a signature of coding efficiency? *Philosophical Transactions of the Royal Society B-Biological Sciences*, 364(1525), 1841-1851. doi: 10.1098/rstb.2009.0026
- Ebner, N. C. (2008). Age of face matters: Age-group differences in ratings of young and old faces. *Behavior Research Methods*, 40(1), 130-136. doi: 10.3758/Brm.40.1.130
- Enns, J. T., Brehaut, J. C., & Shore, D. I. (1999). The duration of a brief event in the mind's eye. *Journal of General Psychology*, 126(4), 355-372.
- Friston, K. (2005). A theory of cortical responses. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360(1456), 815-836. doi: 10.1098/rstb.2005.1622
- Friston, K. (2009). The free-energy principle: a rough guide to the brain? *Trends in Cognitive Sciences*, 13(7), 293-301. doi:10.1016/j.tics.2009.04.005
- Forster, K. I., & Forster, J. C. (2003). A Windows display program with millisecond accuracy. *Behavior Research Methods, Instruments, & Computers*, 35(1), 116-124. doi: 10.3758/Bf03195503
- Gallistel, C.R. (2009). The importance of proving the null. *Psychological Review*, 116(2), 439-453. doi: 10.1037/a0015251
- Gibbon, J., Church, R. M., & Meck, W. H. (1984). Scalar timing in memory. In J. Gibbon & L. Allan (Eds.), *Annals of the New York Academy of Sciences, Volume 423: Timing and time perception*. New York: New York Academy of Sciences.
- Gil, S., & Droit-Volet, S. (2011). "Time flies in the presence of angry faces" ... depending on the temporal task used! *Acta Psychologica*, 136(3), 354-362. doi: 10.1016/j.actpsy.2010.12.010

- Gotts, S.J., Chow, C.C., & Martin, A. (2012). Repetition priming and repetition suppression: A case for enhanced efficiency through neural synchronization. *Cognitive Neuroscience*, 3(3-4), 227-259. doi: 10.1080/17588928.2012.670617
- Grill-Spector, K., Henson, R., & Martin, A. (2006). Repetition and the brain: neural models of stimulus-specific effects. *Trends in Cognitive Sciences*, 10(1), 14-23. doi: 10.1016/j.tics.2005.11.006
- Grondin, S. (2012). Violation of the scalar property for time perception between 1 and 2 seconds: Evidence from interval discrimination, reproduction, and categorization. *Journal of Experimental Psychology: Human Perception and Performance*, 38(4), 880-890. doi: 10.1037/A0027188
- Grotheer, M., & Kovács, G. (2014). Repetition probability effects depend on prior experiences. *Journal of Neuroscience*, 34(19), 6640-6646. doi: 10.1523/JNEUROSCI.5326-13.2014
- Gu, B-M., van Rijn, H., & Meck, W.H. (in press). Oscillatory multiplexing of population codes for interval timing and working memory. *Neuroscience & Biobehavioral Reviews*.
- Huang, Y., & Rao, R.P.N. (2011). Predictive coding. *Wires Interdisciplinary Reviews: Cognitive Science*, 2, 580-593. doi: 10.1002/wcs.142
- Huber, D. E. (2008). Immediate priming and cognitive aftereffects. *Journal of Experimental Psychology: General*, 137(2), 324-347. doi: 10.1037/0096-3445.137.2.324
- Ivry, R.B., & Schlerf, J.E. (2008). Dedicated and intrinsic models of time perception. *Trends in Cognitive Science*, 12(7), 273-280. doi: 10.1016/j.tics.2008.04.002
- Jacoby, L.L. (1983). Perceptual enhancement: Persistent effects of an experience. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 9(1), 21-38.
- Jacoby, L. L., & Whitehouse, K. (1989). An illusion of memory: False recognition influenced by unconscious perception. *Journal of Experimental Psychology: General*, 118(2), 126-135. doi: 10.1037/0096-3445.118.2.126
- Johnston, A., Arnold, D.H., & Nishida, S. (2006). Spatially localized distortions of event time. *Current Biology*, 16, 472-479. doi: 10.1016/j.cub.2006.01.032
- Jones, L. A., Poliakoff, E., & Wells, J. (2009). Good vibrations: Human interval timing in the vibrotactile modality. *Quarterly Journal of Experimental Psychology*, 62(11), 2171-2186. doi: 10.1080/17470210902782200
- Jones, M. R., & Boltz, M. (1989). Dynamic attending and responses to time. *Psychological Review*, 96(3), 459-491. doi: 10.1037//0033-295x.96.3.459

- Kaliukhovich, D. A., & Vogels, R. (2011). Stimulus repetition probability does not affect repetition suppression in macaque inferior temporal cortex. *Cerebral Cortex*, *21*(7), 1547-1558. doi: 10.1093/cercor/bhq207
- Kiebel, S. J., Daunizeau, J., & Friston, K. J. (2008). A hierarchy of time-scales and the brain. *PLOS Computational Biology*, *4*(11), Article e10000209, 1-12. doi: 10.1371/journal.pcbi.1000209
- Kim, E., & McAuley, J. D. (2013). Effects of pitch distance and likelihood on the perceived duration of deviant auditory events. *Attention, Perception, & Psychophysics*, *75*(7), 1547-1558. doi: 10.3758/s13414-013-0490-5
- Kinoshita, S., Foster, K.I., & Mozer, M.C. (2008). Unconscious cognition isn't that smart: Modulation of masked repetition priming effect in the word naming task. *Cognition*, *107*(2), 623-649. doi: 10.1016/j.cognition.2007.11.011
- Kononowicz, T.W., & van Rijn, H. (2014). Decoupling interval timing and climbing neural activity: A dissociation between CNV and N1P2 amplitudes. *Journal of Neuroscience*, *34*(8), 2931-2939. doi: 10.1523/JNEUROSCI.2523-13.2014
- Kovács, G., Iffland, L., Vidnyánszky, Z., & Greenlee, M. W. (2012). Stimulus repetition probability effects on repetition suppression are position invariant for faces. *Neuroimage*, *60*(4), 2128-2135. doi: 10.1016/j.neuroimage.2012.02.038
- Kovács, G., Kaiser, D., Kaliukhovic, D.A., Vidnyánszky, Z., & Vogels, R. (2013). Repetition probability does not affect fMRI repetition suppression for objects. *Journal of Neuroscience*, *33*(23), 9805-9812. doi: 10.1523/JNEUROSCI.3423-12.2013
- Kristjánsson, Á., & Campana, G. (2010). Where perception meets memory: A review of repetition priming in visual search tasks. *Attention, Perception, & Psychophysics*, *72*(1), 5-18. doi: 10.3758/App.72.1.5
- Kruschke, J.K. (2011). Bayesian assessment of null values via parameter estimation and model comparisons. *Perspectives on Psychological Science*, *6*(3), 299-312. doi: 10.1177/1745691611406925
- Kuehl, L.K., Brandt, E.S.L., Hahn, E., Dettling, M., & Neuhaus, A.H. (2013). Exploring the time course of the N170 repetition suppression: A preliminary study. *International Journal of Psychophysiology*, *87*(2), 183-188. doi: 10.1016/j.ijpsycho.2012.12.007
- Large, E. W., & Jones, M. R. (1999). The dynamics of attending: How people track time-varying events. *Psychological Review*, *106*(1), 119-159. doi: 10.1037/0033-295x.106.1.119
- Larsson, J., & Smith, A. T. (2012). fMRI repetition suppression: Neuronal adaptation or stimulus expectation? *Cerebral Cortex*, *22*(3), 567-576. doi: 10.1093/cercor/bhr119

- Lee, T.A., & Mumford, D. (2003). Hierarchical Bayesian inference in the visual cortex. *Journal of the Optical Society of America*, 20(7), 1434-1448.
- Lutig, C., Matell, M.S., & Meck, W.H. (2005). Not “just a coincidence: Fronto-striatal interactions in working memory and interval timing. *Memory*, 13(3/4), 441-448.
- Macar, F., Grondin, S., & Casini, L. (1994). Controlled attention sharing influences time estimation. *Memory & Cognition*, 22(6), 673-686. doi: 10.3758/Bf03209252
- Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, 22(6), 657-672.
- Matell, M. S., & Meck, W. H. (2004). Cortico-striatal circuits and interval timing: coincidence detection of oscillatory processes. *Cognitive Brain Research*, 21(2), 139-170. doi: 10.1016/j.cogbrainres.2004.06.012
- Mattes, S., & Ulrich, R. (1998). Directed attention prolongs the perceived duration of a brief stimulus. *Perception & Psychophysics*, 60(8), 1305-1317. doi: 10.3758/Bf03207993
- Matthews, W. J. (2011a). Can we use verbal estimation to dissect the internal clock? Differentiating the effects of pacemaker rate, switch latencies, and judgment processes. *Behavioural Processes*, 86(1), 68-74. doi: 10.1016/j.beproc.2010.09.006
- Matthews, W. J. (2011b). How do changes in speed affect the perception of duration? *Journal of Experimental Psychology: Human Perception and Performance*, 37(5), 1617-1627. doi: 10.1037/A0022193
- Matthews, W. J. (2011c). Stimulus repetition and the perception of time: The effects of prior exposure on temporal discrimination, judgment, and production. *PLOS ONE*, 6(5), e19815, 19811-19817. doi: 10.1371/journal.pone.0019815
- Matthews, W.J. (2011d). What might judgment and decision making research be like if we took a Bayesian approach to hypothesis testing? *Judgment and Decision Making*, 8, 843-856.
- Matthews, W. J. (2013). How does sequence structure affect the judgment of time? Exploring a weighted sum of segments model. *Cognitive Psychology*, 66(3), 259-282. doi: 10.1016/j.cogpsych.2013.01.001
- Matthews, W.J., & Dylman, A.S. (2014). The language of magnitude comparison. *Journal of Experimental Psychology: General*, 143(2), 510-520. doi: 10.1037/a0034143
- Matthews, W.J., & Grondin, S. (2012). On the replication of Kristofferson’s (1980) quantal timing for duration discrimination: some learning but no quanta and not much of a Weber constant. *Attention, Perception, & Psychophysics*, 74, 1056-1072. Doi: 10.3758/s13414-012-0282-3
- Matthews, W.J., & Meck, W.H. (2014). Time perception: the bad news and the good. *WIREs Cognitive Science*, 5, 429-446. doi: 10.1002/wcs.1298

- Matthews, W.J., & Stewart, N. (2009). The effect of interstimulus interval on sequential effects in absolute identification. *Quarterly Journal of Experimental Psychology*, *62*(10), 2014-2029. doi: 10.1080/17470210802649285
- Matthews, W. J., Stewart, N., & Wearden, J. H. (2011). Stimulus intensity and the perception of duration. *Journal of Experimental Psychology: Human Perception and Performance*, *37*(1), 303-313. doi: 10.1037/A0019961
- Matthews, W.J., Terhune, D.B., van Rijn, H. Eagleman, D.M., Sommer, M.A., & Meck, W.H. (in press). Subjective duration as a signature of coding efficiency: Emerging links among stimulus repetition, predictive coding, and cortical GABA levels. *Timing & Time Perception Reviews*.
- Mauk, M. D., & Buonomano, D. V. (2004). The neural basis of temporal processing. *Annual Review of Neuroscience*, *27*, 307-340. doi: 10.1146/annurev.neuro.27.070203.144247
- Mayrhauser, L., Bergmann, J., Crone, J., & Kronbichler, M. (2014). Neural repetition suppression: evidence for perceptual expectation in object-selective regions. *Frontiers in Human Neuroscience*, *8*, Article 225. 1-8. doi: 10.3389/fnhum.2014.00225
- Merchant, H., Harrington, D. L., & Meck, W. H. (2013). Neural basis of the perception and estimation of time. *Annual Review of Neuroscience*, *36*, 313-336. doi: 10.1146/annurev-neuro-062012-170349
- Merchant, H., Zarco, W., & Prado, L. (2008). Do we have a common mechanism for measuring time in the hundreds of millisecond range? Evidence from multiple-interval timing tasks. *Journal of Neurophysiology*, *99*, 939-949. doi: 10.1152/jn.01225.2007
- Minear, M., & Park, D. C. (2004). A lifespan database of adult facial stimuli. *Behavior Research Methods, Instruments, & Computers*, *36*(4), 630-633. doi: 10.3758/Bf03206543
- Morey, R.D., Rouder, J.N., & Jamil, T. (2014). BayesFactor: Computation of Bayes factors for common designs. R package version 0.9.8.
- Neely, J.H. (1991). Semantic priming effects in visual word recognition: A selective review of current findings and theories. In D. Besner & G.W. Humphreys (Eds.), *Basic processes in reading: Visual word recognition* (pp. 264-336). Hillsdale, NJ: Erlbaum.
- New, J. J., & Scholl, B. J. (2009). Subjective time dilation: Spatially local, object-based, or a global visual experience? *Journal of Vision*, *9*(2), 4, 1-11. doi: 10.1167/9.2.4
- Noguchi, Y., & Kakigi, R. (2006). Time representations can be made from nontemporal information in the brain: An MEG study. *Cerebral Cortex*, *16*(12), 1797-1808. doi: 10.1093/cercor/bhj117
- O'Toole, A. J., Harms, J., Snow, S. L., Hurst, D. R., Pappas, M. R., Ayyad, J. H., & Abdi, H. (2005). A video database of moving faces and people. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *27*(5), 812-816. doi: 10.1109/Tpami.2005.90

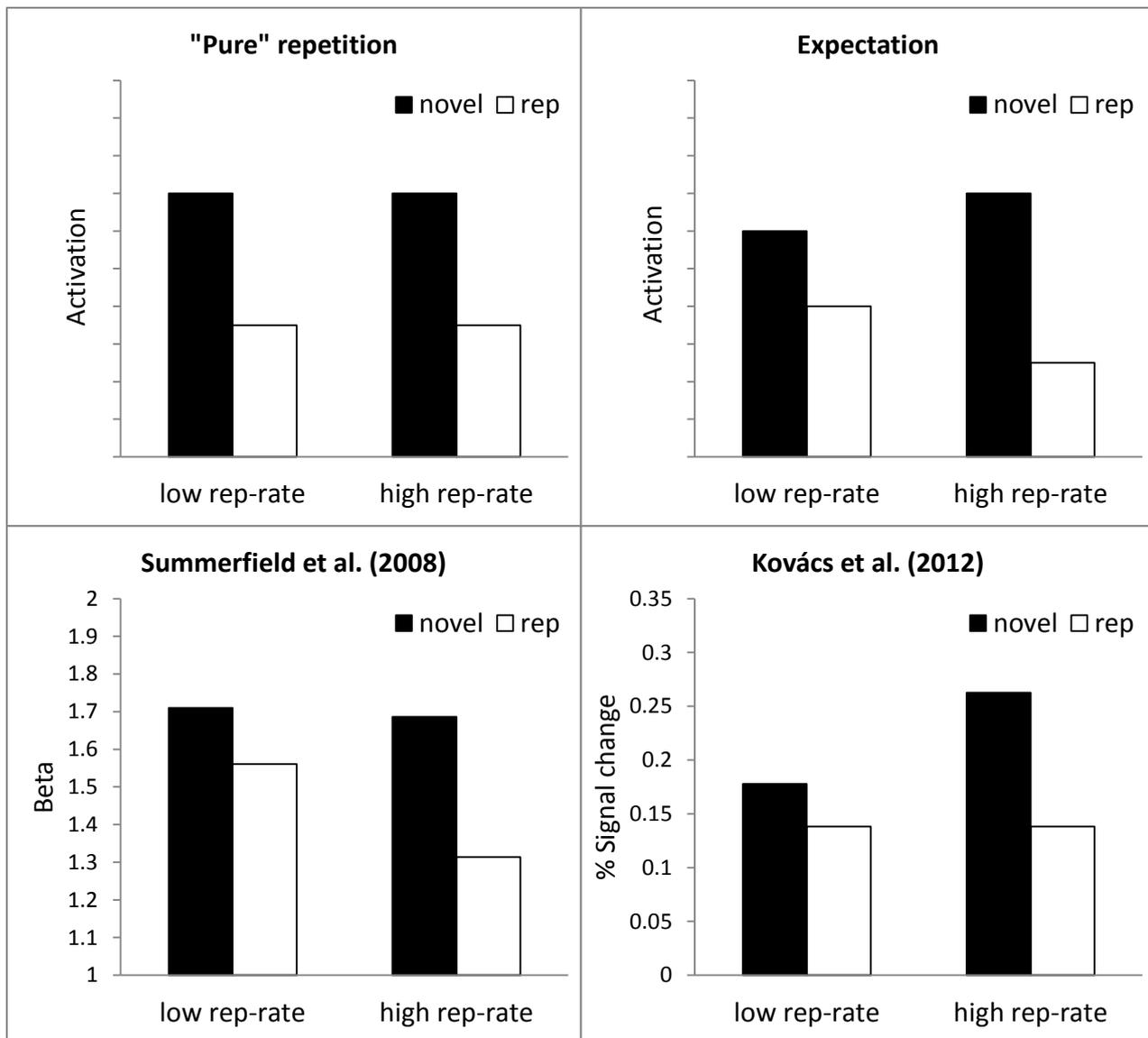
- Ono, F., & Kawahara, J. (2005). The effect of unconscious priming on temporal production. *Consciousness and Cognition*, *14*(3), 474-482. doi: 10.1016/j.concog.2005.02.001
- Pariyadath, V., & Eagleman, D. (2007). The effect of predictability on subjective duration. *Plos One*, *2*(11), e1264, 1261-1266. doi: 10.1371/Journal.Pone.0001264
- Pariyadath, V., & Eagleman, D. M. (2012). Subjective duration distortions mirror neural repetition suppression. *Plos One*, *7*(12), e49362, 49361-49364. doi: 10.1371/journal.pone.0049362
- Rammsayer, T., & Ulrich, R. (2001). Counting models of temporal discrimination. *Psychonomic Bulletin & Review*, *8*(2), 270-277.
- Rao, R. P. N., & Ballard, D. H. (1999). Predictive coding in the visual cortex: A functional interpretation of some extra-classical receptive-field effects. *Nature Neuroscience*, *2*(1), 79-87. doi: 10.1038/4580
- Rose, D., & Summers, J. (1995). Duration illusions in a train of visual stimuli. *Perception*, *24*(10), 1177-1187. doi: 10.1068/P241177
- Rouder, J.N., Speckman, P.L., Sun, D., Morey, R.D., & Iverson, G. (2009). Bayesian *t* tests for accepting and rejecting the null hypothesis. *Psychonomic Bulletin & Review*, *16*(2), 225-237. doi: 10.3758/PBR.16.2.225
- Sadeghi, N.G., Pariyadath, V., Apte, S., Eagleman, D.M., & Cook, E.P. (2011). Neural correlates of subsecond time distortion in the middle temporal area of visual cortex. *Journal of Cognitive Neuroscience*, *23*(12), 3829-3840. doi: 10.1162/jocn\_a\_00071
- Scarborough, D. L., Cortese, C., & Scarborough, H. S. (1977). Frequency and repetition effects in lexical memory. *Journal of Experimental Psychology: Human Perception and Performance*, *3*(1), 1-17. doi: 10.1037/0096-1523.3.1.1
- Schacter, D.L., Addis, D.R., & Buckner, R.L. (2007). Remembering the past to imagine the future: The prospective brain. *Nature Reviews Neuroscience*, *8*, 657-661. doi:10.1038/nrn2213
- Schiffman, H.R., & Bobko, D.J. (1974). Effects of stimulus complexit on the perception of brief temporal intervals. *Journal of Experimental Psychology*, *103*(1), 156-159.
- Schindel, R., Rowlands, J., & Arnold, D. H. (2011). The oddball effect: Perceived duration and predictive coding. *Journal of Vision*, *11*(2), 17, 11-19. doi: 10.1167/11.2.17
- Seifried, T., & Ulrich, R. (2010). Does the asymmetry effect inflate the temporal expansion of odd stimuli? *Psychological Research*, *74*(1), 90-98. doi: 10.1007/s00426-008-0187-x
- Shi, Z., Church, R.M., & Meck, W.H. (2013). Bayesian optimization of time perception. *Trends in Cognitive Sciences* *17*(11), 556-564. doi: 10.1016/j.tics.2013.09.009
- Stewart, N., Brown, G.D.A., & Chater, N. (2005). Absolute identification by relative judgment. *Psychological Review*, *112*(4), 881-911. doi: 10.1037/0033-295X.112.4.881

- Stewart, N., & Matthews, W.J. (2009). Relative judgment and knowledge of the category structure. *Psychonomic Bulletin & Review*, *16*(3), 594-599. doi: 10.3758/PBR.16.3.594
- Summerfield, C., & Egner, T. (2009). Expectation (and attention) in visual cognition. *Trends in Cognitive Sciences*, *13*(9), 403-409. doi: 10.1016/j.tics.2009.06.003
- Summerfield, C., Trittschuh, E. H., Monti, J. M., Mesulam, M. M., & Egner, T. (2008). Neural repetition suppression reflects fulfilled perceptual expectations. *Nature Neuroscience*, *11*(9), 1004-1006. doi: 10.1038/Nn.2163
- Summerfield, C., Wyart, V., Johnen, V.M., & de Gardelle, V. (2011). Human scalp electropencephalography reveals that repetition suppression varies with expectation. *Frontiers in Human Neuroscience*, *5*, Article 67, 1-13.
- Taatgen, N., & van Rijn, H. (2011). Traces of times past: Representations of temporal intervals in memory. *Memory & Cognition*, *39*(8), 1546-1560. doi: 10.3758/s13421-011-0113-0
- Tenenbaum, J.B., Kemp, C., Griffiths, T.L., & Goodman, N.D. (2011). How to grow a mind: Statistics, structure, and abstraction. *Science*, *331*, 1279-1285. doi: 10.1126/science.1192788
- Todorovic, A., & de Lange, F. P. (2012). Repetition suppression and expectation suppression are dissociable in time in early auditory evoked fields. *Journal of Neuroscience*, *32*(39), 13389-13395. doi: 10.1523/Jneurosci.2227-12.2012
- Todorovic, A., van Ede, F., Maris, E., & de Lange, F. P. (2011). Prior expectation mediates neural adaptation to repeated sounds in the auditory cortex: An MEG study. *Journal of Neuroscience*, *31*(25), 9118-9123. doi: 10.1523/Jneurosci.1425-11.2011
- Treisman, M. (1963). Temporal discrimination and the indifference interval: Implications for a model of the "internal clock". *Psychological Monographs*, *77*(13), 1-31.
- Tse, P. U., Intriligator, J., Rivest, J., & Cavanagh, P. (2004). Attention and the subjective expansion of time. *Perception & Psychophysics*, *66*(7), 1171-1189. doi: 10.3758/Bf03196844
- Ulrich, R., Nitschke, J., & Rammsayer, T. (2006). Perceived duration of expected and unexpected stimuli. *Psychological Research*, *70*(2), 77-87. doi: 10.1007/S00426-004-0195-4
- Van Rijn, H., Gu, B-M., & Meck, W.H. (in press). Dedicated clock/timing-circuit theories of time perception and timed performance. In H. Merchant & V. de Lafuente (Eds.). *Neurobiology of interval timing*. New York: Springer-Verlag.
- Varakin, D.A., Klemes, K.J., & Porter, K.A. (2013). The effect of scene structure on time perception. *Quarterly Journal of Experimental Psychology*, *66*(8), 1639-1652. doi: 10.1080/17470218.2012.754912
- Wacongne, C., Labyt, E., van Wassenhove, V., Bekinschtein, T., Naccache, L., & Dehaene, S. (2011). Evidence for a hierarchy of predictions and prediction errors in human cortex. *Proceedings*

- of the National Academy of Sciences of the United States of America, 108(51), 20754-20759.  
doi: 10.1073/pnas.1117807108
- Wearden, J. H. (1992). Temporal generalization in humans. *Journal of Experimental Psychology: Animal Behavior Processes*, 18(2), 134-144. doi: 10.1037//0097-7403.18.2.134
- Wearden, J. H. (1999). "Beyond the fields we know ...": exploring and developing scalar timing theory. *Behavioural Processes*, 45(1-3), 3-21. doi: 10.1016/S0376-6357(99)00006-6
- Wearden, J. H., Edwards, H., Fakhri, M., & Percival, A. (1998). Why "sounds are judged longer than lights": Application of a model of the internal clock in humans. *Quarterly Journal of Experimental Psychology*, 51B(2), 97-120.
- Witherspoon, D., & Allan, L. G. (1985). The effect of a prior presentation on temporal judgments in a perceptual identification task. *Memory & Cognition*, 13(2), 101-111. doi: 10.3758/Bf03197003
- Xuan, B., Zhang, D., He, S., & Chen, X. C. (2007). Larger stimuli are judged to last longer. *Journal of Vision*, 7(10), 2, 1-5. doi: 10.1167/7.10.2
- Zajonc, R. B. (1968). Attitudinal effects of mere exposure. *Journal of Personality and Social Psychology*, 9(2), 1-27. doi: 10.1037/H0025848
- Zakay, D., & Block, R. A. (1997). Temporal cognition. *Current Directions in Psychological Science*, 6(1), 12-16. doi: 10.1111/1467-8721.Ep11512604
- Zucker, R.S., & Regehr, W.G. (2002). Short-term synaptic plasticity. *Annual Review of Physiology*, 64, 355-405. doi: 10.1146/annurev.physiol.64.092501.114547

Table 1. Means and standard deviations of judgments for each condition of Experiment 3.

Duration	Low rep-rate		High rep-rate	
	novel	repeat	novel	repeat
906 ms	949.14 (SD = 73.76)	950.6 (SD = 83.87)	942.46 (SD = 73.06)	955.29 (SD = 68.06)
1000 ms	994.97 (SD = 57.99)	1001.79 (SD = 73.29)	989.09 (SD = 70)	1008.93 (SD = 62.88)
1094 ms	1048.02 (SD = 52.73)	1033.12 (SD = 70.11)	1039.68 (SD = 72.5)	1038.89 (SD = 63.42)



*Figure 1.* The top panels show the predicted magnitude of evoked responses to novel and repeated stimuli when repetitions are rare (low rep-rate) and common (high rep-rate). The left panel indicates the pattern if repetition suppression is purely due to prior exposure to the stimulus; the right panel illustrates the predictions if repetition suppression is due to higher-order expectations. The bottom left panel plots data from Summerfield et al. (2008), showing neural responses in fusiform face area to novel and repeated faces. Repetition suppression is much more pronounced when repetitions are common/predictable, showing that the effect reflects expectations/predictive coding rather than just low-level adaptation. The bottom right panel plots similar results from a study by Kovács et al. (2012); the pattern has been replicated many times elsewhere.

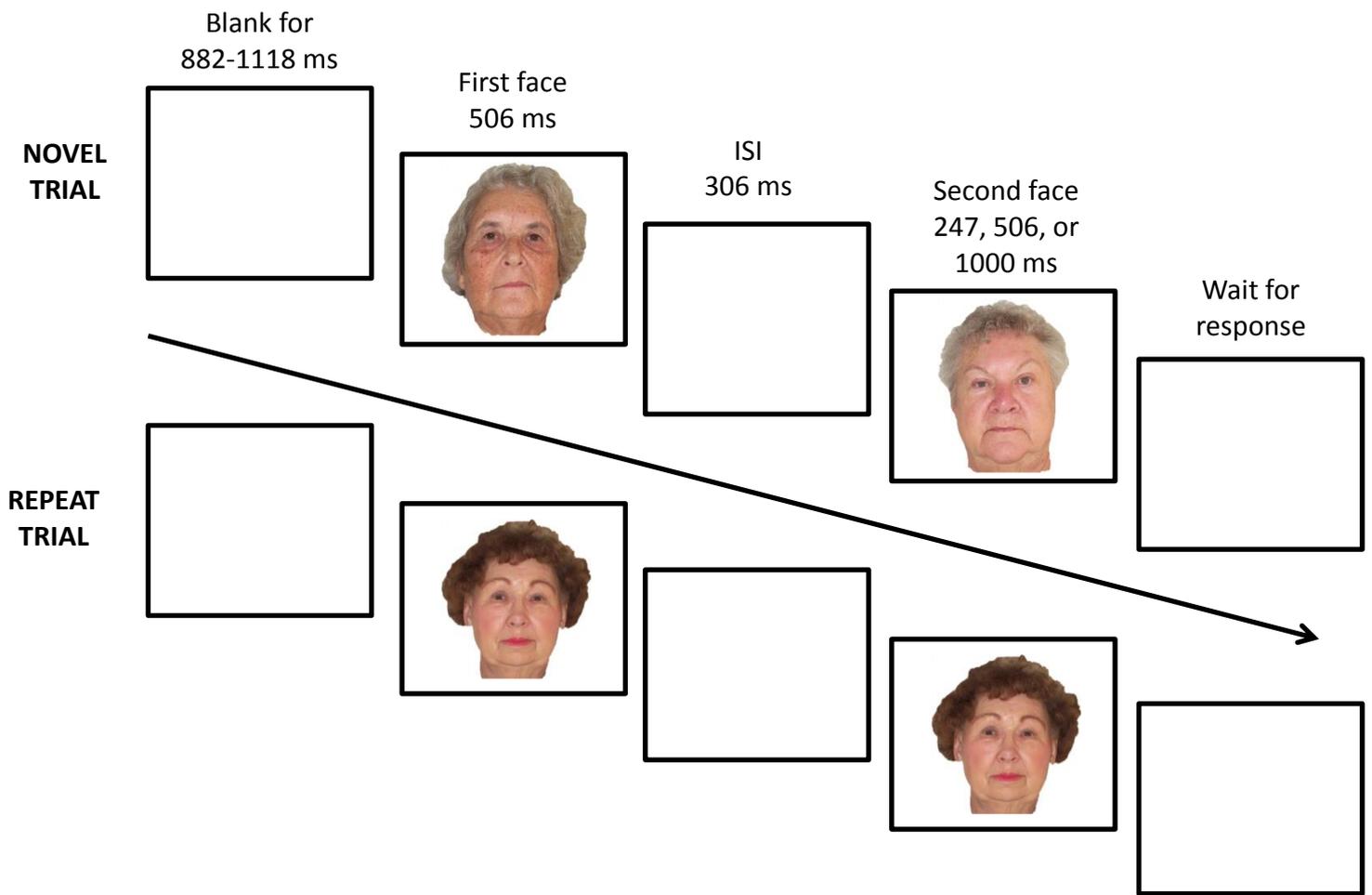


Figure 2. Sequence of events on each trial of Experiment 1. On repeat trials, the two faces were the same; on novel trials they were different.

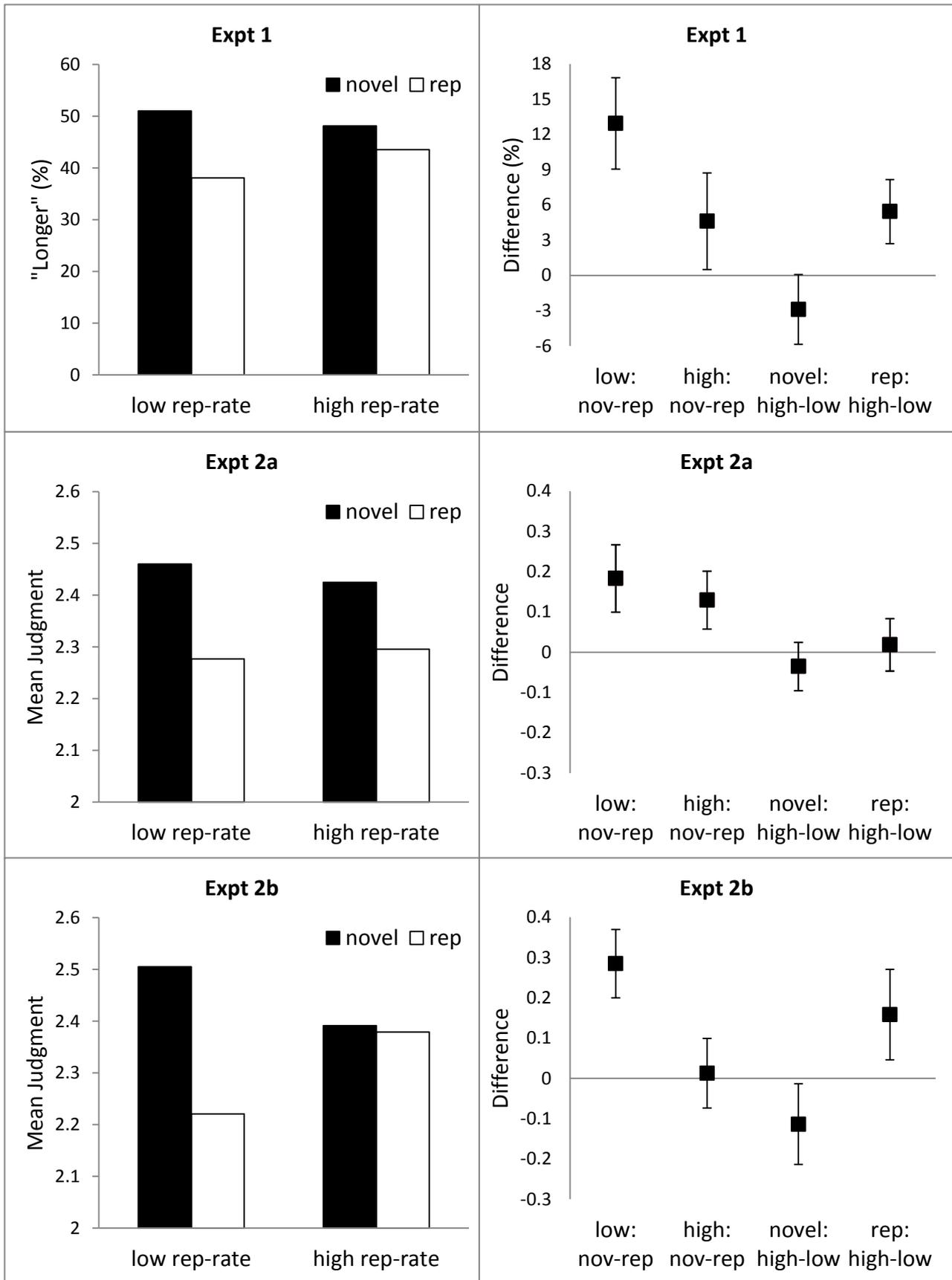


Figure 3. Results from Experiments 1, 2a, and 2b. The left panels show the mean responses in each condition: novel stimuli were judged longer than repeats, but this effect diminished when repeats were more common – the opposite of the effect on neural activity (see Figure 1). The right panels show the pairwise contrasts with 95% confidence intervals: the first two points show the difference

between novel and repeated stimuli for the low and high rep-rate conditions; the next two points show the effect of changing the rep-rate on judgments of novel and repeated stimuli.

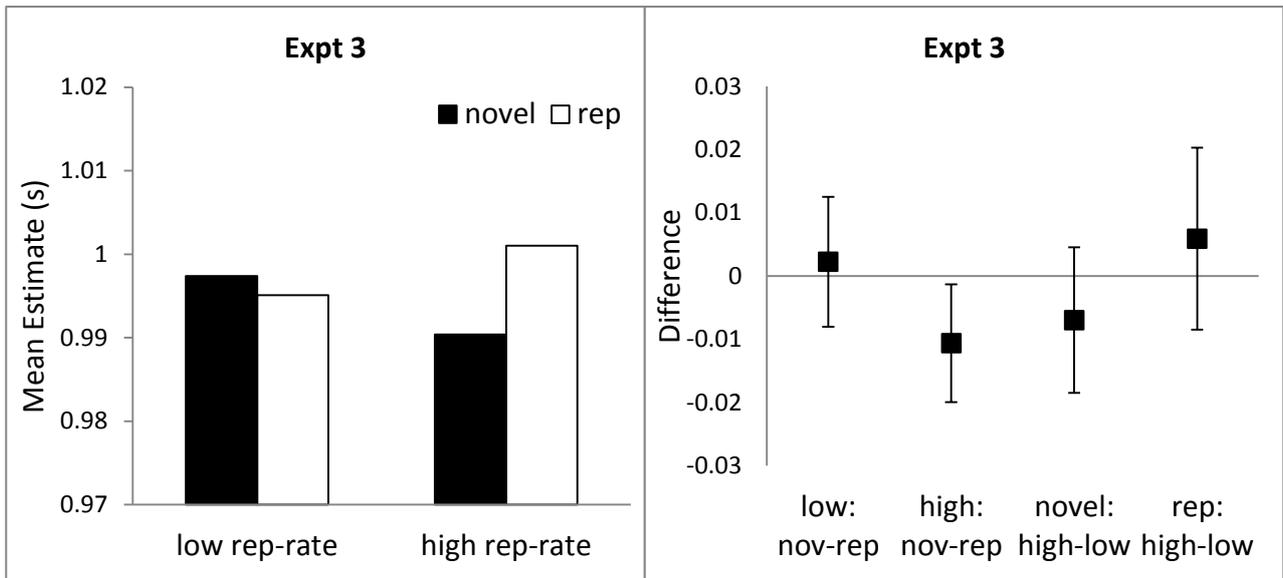


Figure 4. Results from Experiment 3. The left panel plots the mean judgments in each condition; the right panel shows pairwise contrasts with 95% confidence intervals, as before.

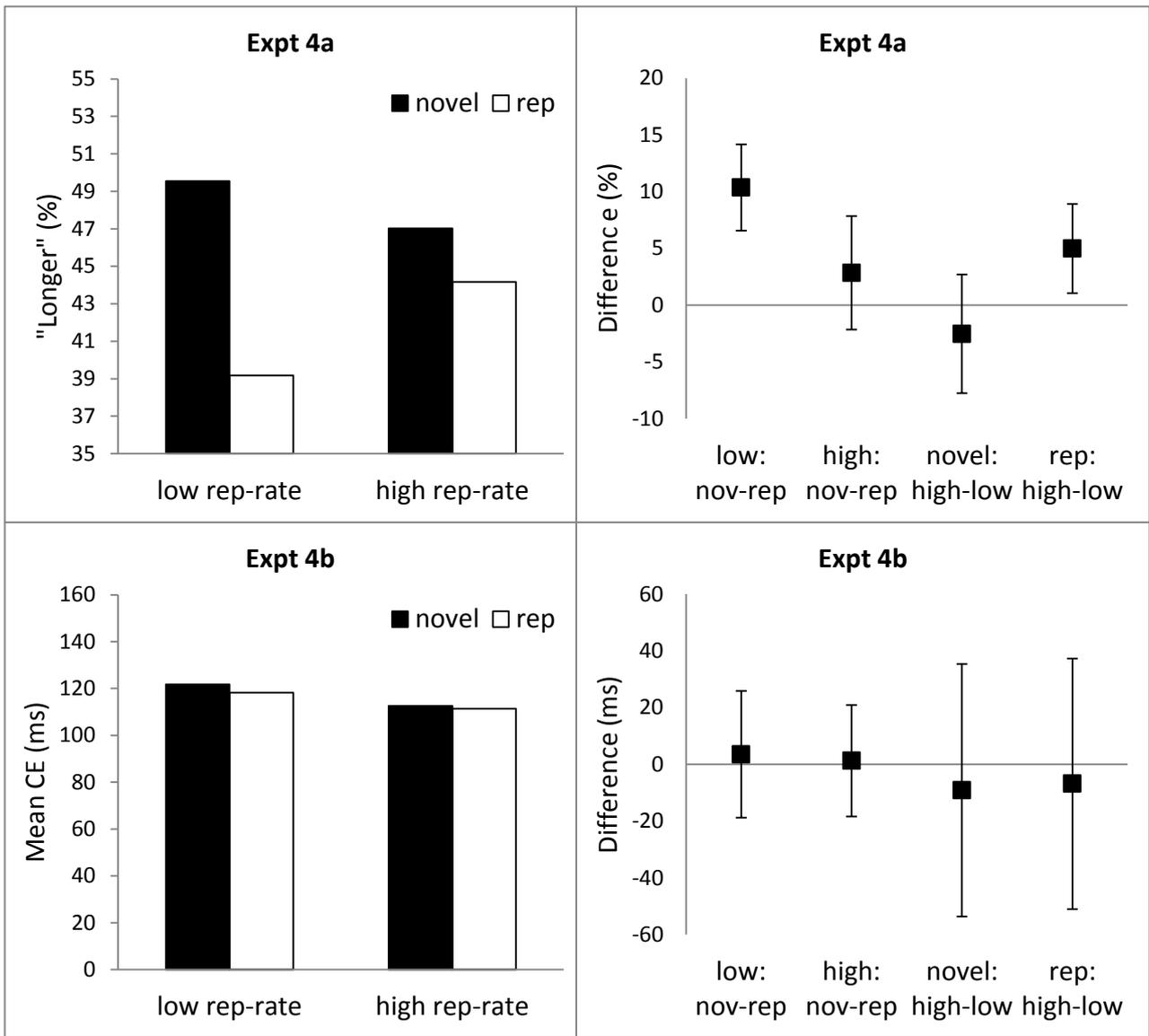
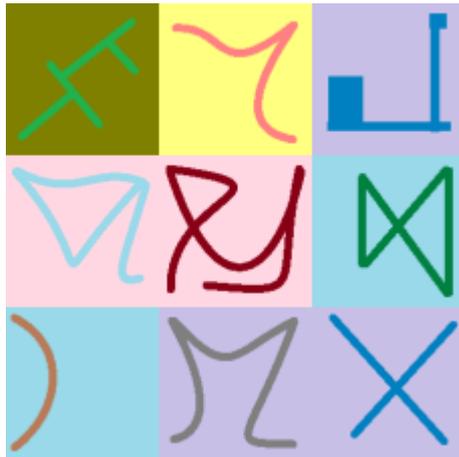


Figure 5: Results from Experiments 4a and 4b. The left hand panels show the mean responses for each condition; the right panels show the pairwise contrasts with 95% confidence intervals. Experiment 4a replicates the pattern found in previous experiments; Experiment 4b shows no effect of repetition or repetition frequency.



*Figure 6.* An example of the abstract stimuli used in Experiments 5 and 6. In Experiment 5, each stimulus was produced by sampling 9 different icons from a pool of 75. On novel trials, the first and second stimuli on each trial were different. In Experiment 6, “complex” stimuli were constructed in the same way as in Experiment 5; “simple” stimuli were constructed by repeating the same icon 9 times in the 3x3 grid.

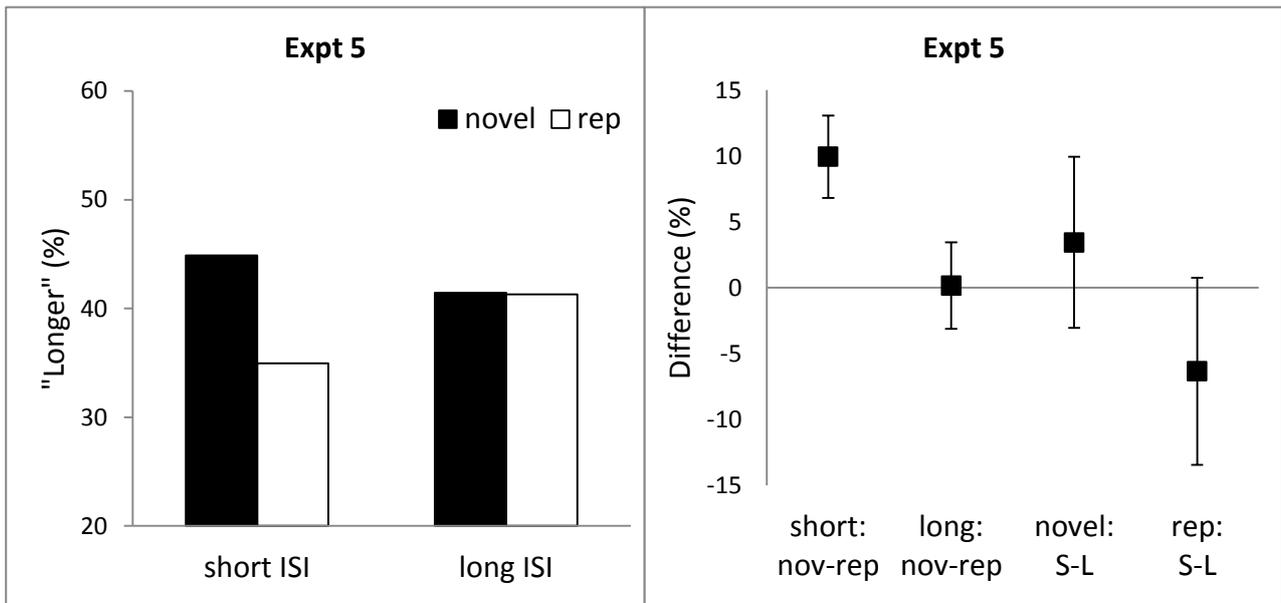


Figure 7. Results of Experiment 5. The left panel shows the mean proportion of trials on which the comparison stimulus was judged to last longer than the standard as a function of whether the image was a repeat or novel and whether the ISI was short (306 ms) or long (2000 ms). The right panel shows the contrasts, with 95% confidence intervals (S = short ISI; L = long ISI).

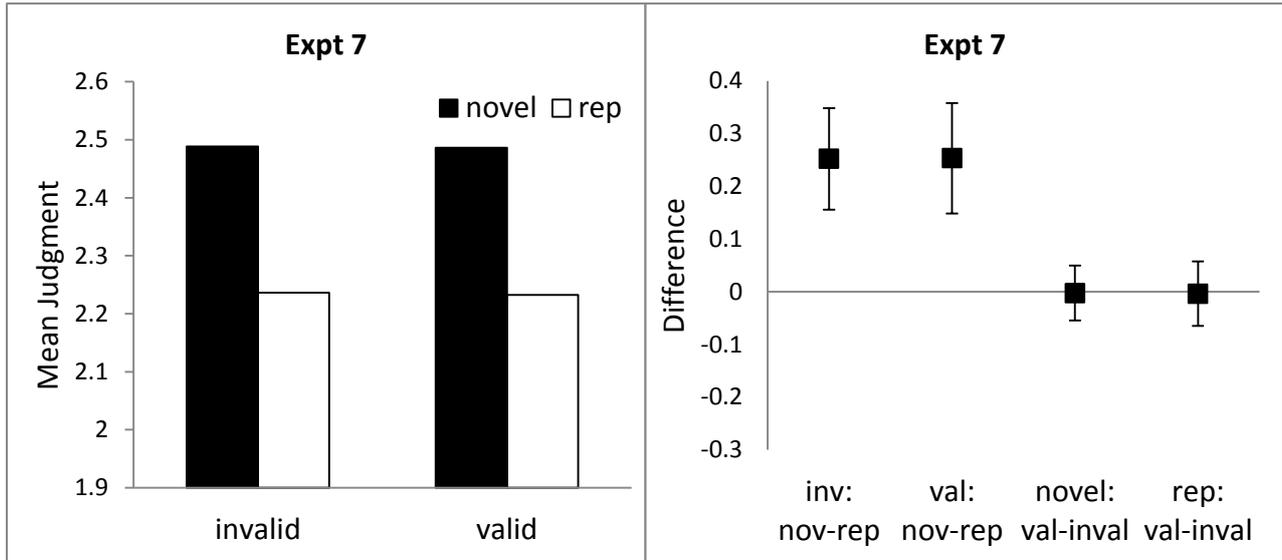


Figure 8. Results of Experiment 7. The left panels show the mean judgments for each condition; the right panels show the pairwise contrasts with 95% confidence intervals. “Valid” trials began with a cue that perfectly predicted whether or not the forthcoming faces would be identical. On “invalid” trials, the cue that preceded the face pair conveyed no information about repetition.

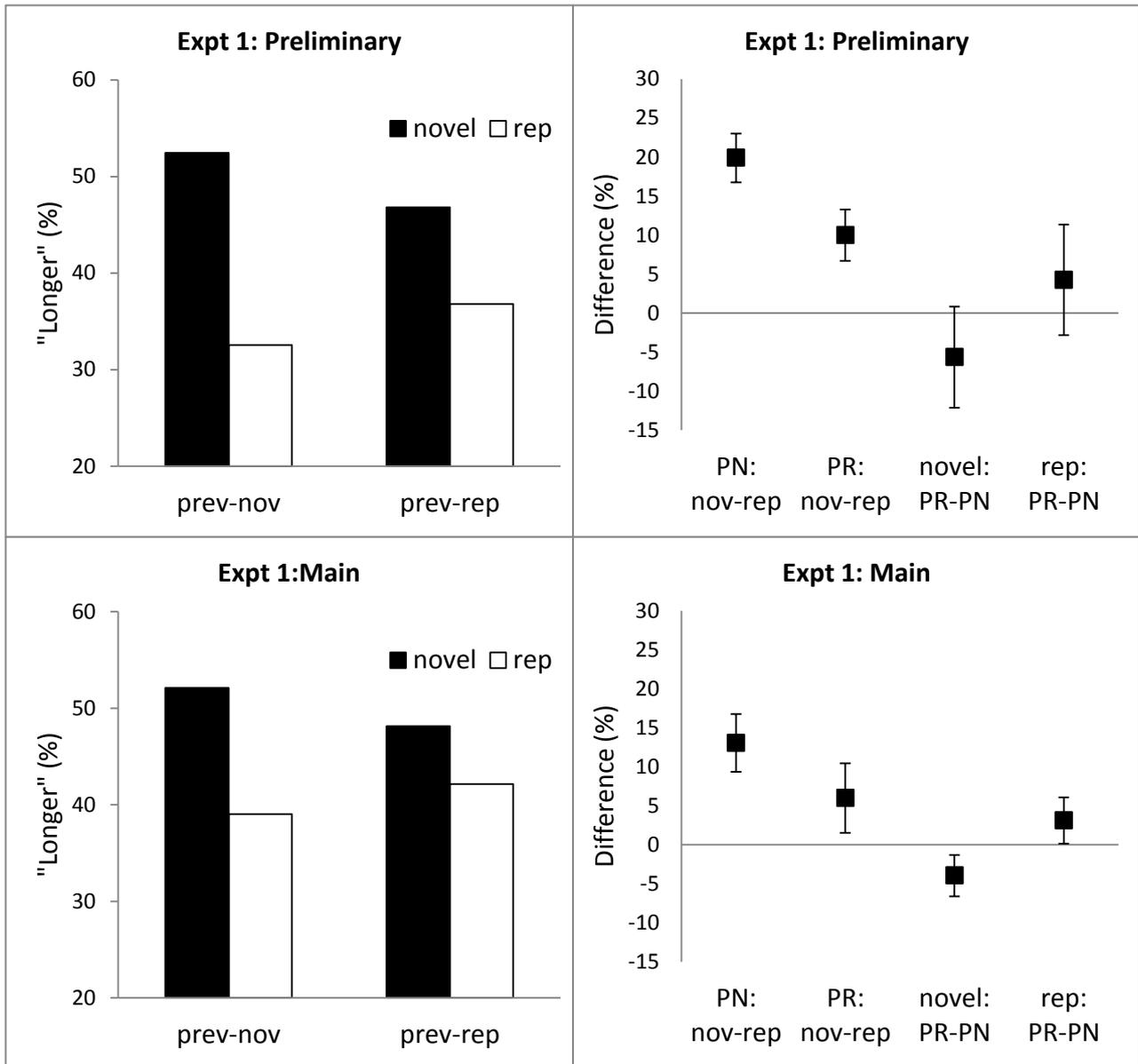


Figure 9. Sequential effects in Experiment 1. The left panels show the mean judgments as a function of the current image (novel or repeat) and the preceding trial-type (prev-nov = on the previous trial, the comparison stimulus was novel; prev-rep = on the previous trial, the comparison stimulus was a repeat of the standard). The right panels show the contrasts with 95% confidence intervals. In these plots, PN = previous trial was novel; PR = previous trial was a repeat. (Thus, for example, PR: nov-rep indicates the difference between novel and repeat stimuli on the current trial when the previous trial was a repeat. Likewise, novel: PR-PN indicates the difference between judgments of novel stimuli on the current trial when the previous trial was a repeat vs judgments of novel stimuli on the current trial when the previous trial was novel).

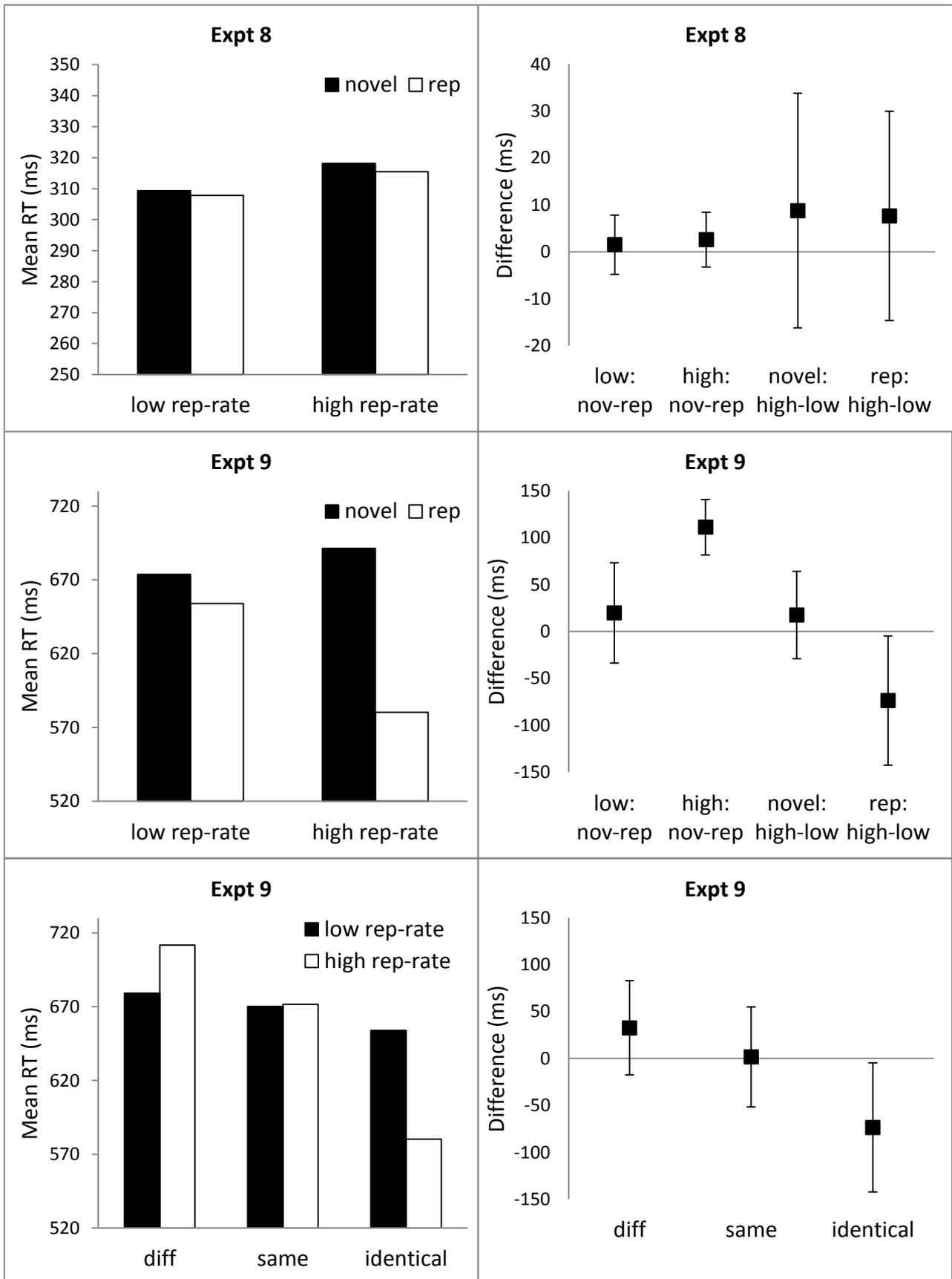


Figure 10. Results of Experiments 8 and 9, showing mean responses (left panels) and pairwise contrasts with 95% confidence intervals (right panels). The top row shows the results from the

onset-detection task of Experiment 8. The middle row shows how gender classification responses for repeated images become faster as the repetition rate increases. The bottom row shows that this effect is specific to trials where the second image is identical to the first, and does not generalize to novel faces of the same gender-- arguing against a pure response-preparation account.