When Temporal Certainty Doesn't Help

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Abstract

■ In a dynamically changing environment, the ability to capture regularities in our sensory input helps us generate predictions about future events. In most sensory systems, the basic finding is clear: Knowing when something will happen improves performance on it [Nobre, A. C., & van Ede, F. (2017). Anticipated moments: Temporal structure in attention. *Nature Reviews Neuroscience*, *19*, 34–48, 2017]. We here examined the impact of temporal predictions on a less-explored modality: touch. Participants were instructed to detect a brief target embedded in an ongoing vibrotactile stimulus. Unbeknownst to them, the experiment had two timing conditions: In one part, the time of target onset was fixed and thus temporally predictable, whereas in the other, it could appear at a random time within the ongoing stimulation. We found a clear modulation of detection thresholds due to temporal predictability: Contrary to other sensory systems, detecting a predictable tactile target was worse relative to unpredictable targets. We discuss our findings within the framework of tactile suppression. ■

INTRODUCTION

We are continuously exposed to a rich and dynamically changing environment. Our ability to capture regularities and patterns in our sensory input helps us generate predictions about future events. In most sensory systems, the basic finding is clear: Knowing when something will happen improves performance on it. We are more likely to perceive or efficiently respond to an upcoming event if we know when to harness our limited resources to it (see Nobre & van Ede, 2017, for a review).

The benefits of spatial, object- and feature-based anticipation have long been shown across the sensory modalities—including in vision (e.g., Prinzmetal, McCool, & Park, 2005; Posner, Cohen, & Rafal, 1982), in audition (Spence & Driver, 1994), and in touch (see Gomez-Ramirez, Hysaj, & Niebur, 2016, for a review)—and manifest as improved sensory processing and motor preparation, decreased RTs, and increased precision (e.g., perceptual accuracy; Carrasco, 2011; Miniussi, Wilding, Coull, & Nobre, 1999; Coull & Nobre, 1998; Posner, Snyder, & Davidson, 1980).

Temporal anticipation, on the other hand, has been relatively less explored despite the prevalence of temporal patterns in our environment, including rhythms and regularities (Haegens & Zion Golumbic, 2018; Nobre & Van Ede, 2017; Herbst & Landau, 2016; Schroeder & Lakatos, 2009; Correa & Nobre, 2008; Jones, Moynihan, MacKenzie, & Puente, 2002). We continuously form predictions regarding the onset or duration of upcoming events (e.g., a changing traffic light) based on temporal contingencies that we effortlessly and without awareness extract from our surroundings. These contingencies allow us, as in the case of other types of predictions (i.e., about locations or object features), to orient our attention to the moment in which an event is expected to occur.

Previous studies on temporal anticipation have typically used visual or auditory detection and discrimination tasks with short-duration, near-threshold stimuli presented within fixed temporal structures of several types, including associations (i.e., foreperiod paradigms), rhythms, and sequences (see Nobre & van Ede, 2018, for a review). All have revealed enhanced sensory or motor processing for predictable versus randomly occurring events (Rohenkohl, Gould, Pessoa, & Nobre, 2014; Rohenkohl, Cravo, Wyart, & Nobre, 2012; Davranche, Nazarian, Vidal, & Coull, 2011; Nobre, Correa, & Coull, 2007); predictable events elicit decreased RTs, improved accuracy (in both detection and discrimination tasks), heightened sensitivity (as measured by signal detection theory [SDT]; i.e., d'), and enhanced sensory psychophysical parameters (i.e., lower visual thresholds; Fernández, Denison, & Carrasco, 2019; Denison, Heeger, & Carrasco, 2017; Samaha, Bauer, Cimaroli, & Postle, 2015; Rohenkohl et al., 2012; Mathewson, Fabiani, Gratton, Beck, & Lleras, 2010; Correa & Nobre, 2008; Correa, Lupiáñez, & Tudela, 2005). Although the benefits of temporal predictions have been clearly demonstrated in vision as well as audition (Breska & Deouell, 2017; Herbst & Obleser, 2017; Rohenkohl et al., 2012; Mathewson et al., 2010; Correa et al., 2005), their effects on touch have been relatively less explored.

The few studies that have investigated selection processes in the tactile domain often combine temporal orienting with spatial orienting or with orienting across

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Journal of Cognitive Neuroscience 32:2, pp. 315–325
https://doi.org/10.1162/jocn_a_01482

different modalities (Mühlberg & Soto-Faraco, 2019; van Ede, de Lange, Jensen, & Maris, 2011; van Ede, Jensen, & Maris, 2010; Lange & Röder, 2006). Moreover, these studies often focus on RT measures or simple accuracy measures and do not fully characterize perceptual thresholds. Finally, when investigating temporal prediction, performance on a predictable target is often compared with performance when a prediction is violated rather than true temporal uncertainty. When a prediction is violated, any modulation in performance could be the result of uncertainty or the result of surprise. Therefore, it is still unknown how temporal certainty affects perceptual thresholds in the tactile domain (i.e., in the absence of spatial or cross-modal expectations).

One possibility is that all sensory modalities are similarly impacted by temporal predictability—and that the ability to anticipate the timing of an upcoming tactile event also (re)orients our attention in time and improves performance. However, somatosensation is uniquely different from vision and audition in how it typically acquires its inputs: its agency. Rather than passively receiving sensory input, it is often coupled to the sensory consequences of one's actions. In essence, temporal and spatial predictions are contained in the internal representation of the action (i.e., the efference copy) and reside in the somatosensory system. For example, drinking a cup of coffee, getting dressed, typing, and shaking someone's hand are all self-generated actions that directly result in, or cause, the ensuing tactile input. Therefore, another possibility is that touch is more efficiently tuned to unpredictable events, prone to tracking changes in our environment rather than optimized for responding to predictable events, many of which we ourselves produce as we go about our daily lives. We thus examined the impact of temporal predictions on the tactile modality. To hone in on the role of temporal predictions in somatosensation in the absence of a motor plan, we designed a purely sensory experiment.

In this study, we embedded a detection target in an ongoing vibrotactile stimulation. The detection target was a brief (0.04-sec) intensity decrement within a relatively long (1.6-sec) vibrotactile stimulation that was presented to participants' dominant index finger (see Figure 1A and 1B). Participants had to detect this target, which unbeknown to them could appear either at predictable or random times within the ongoing stimulation (in separate experimental blocks). In addition, we ran a control experiment in which we administered an equivalent stimulus and detection task but delivered to the auditory modality (see Figure 1C and 1D). We thus examined the role of implicit temporal expectations in the tactile modality.

METHODS

Experiment 1

Participants

We prespecified a sample size of 20 participants based on previous psychophysical and temporal expectation studies. Twenty-two healthy participants took part in a psychophysical experiment for payment or class credit. One participant was excluded because of a technical problem. No participants were excluded because of poor performance. Data are presented for 21 participants (ages 19–28 years, average = 23 years; 19 women; 19 right-handed).

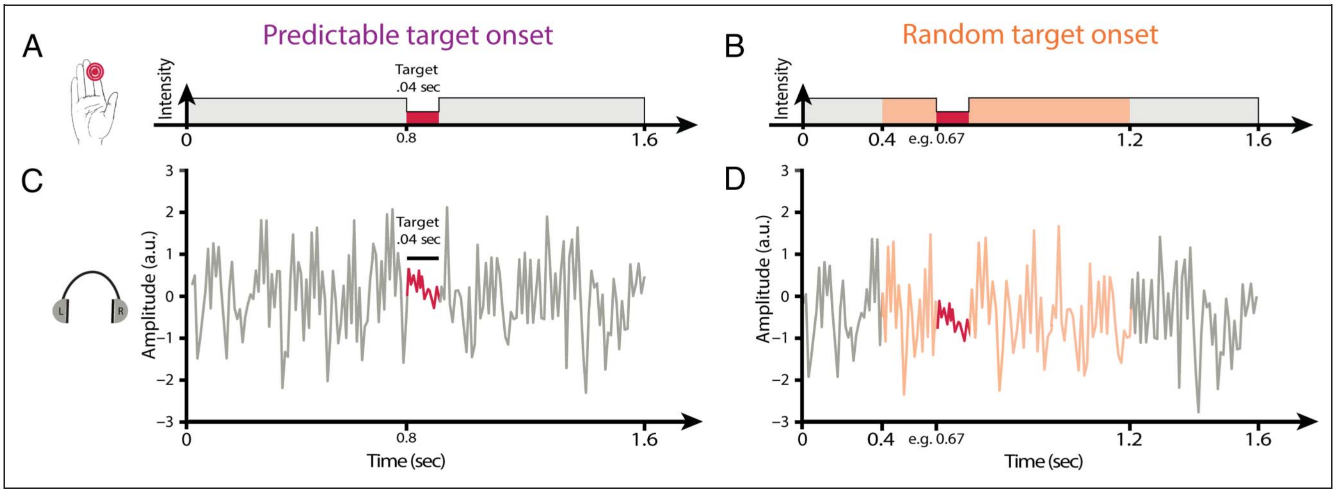

Figure 1. Experimental stimuli in Experiment 1 (tactile; A, B), participants received ongoing (1.6-sec) vibrotactile stimulation to the index finger of their dominant hand. The target, a 0.04-sec decrease in intensity, was embedded in half of the trials (50% catch trials, 560–720 total trials). The intensity decrements varied parametrically, resulting in seven target levels ranging from hardly to easily detectable. After the end of the 1.6-sec stimulation, participants were prompted to indicate via a key-press whether or not they had detected the target. In Experiment 2 (auditory; C, D), participants listened to ongoing (1.6-sec) streams of white noise presented binaurally through headphones. The target was also a 0.04-sec embedded decrease in intensity, and all temporal and experimental parameters were identical to Experiment 1. In the predictable timing part of the experiment (A, C), the target always appeared halfway (0.8 sec) through the stimulation or stream of white noise. In the random timing part of the experiment (B, D), the target could appear randomly at any time point within a 0.8-sec time window (denoted in orange).

Participants signed a consent form before experimentation, and the study was approved by the institutional review board of human experimentation at The Hebrew University of Jerusalem.

Apparatus

Stimulation was produced with a vibrotactile coin stimulator connected to an open-source hardware, Arduino (Uno Rev3), programmed with C++ on compatible IDE. The experiment was built and run on OpenSesame v3.1 (Mathôt, Schreij, & Theeuwes, 2012). The vibration produced by the Arduino was approximately 120 Hz. Headphones were used to administer white noise throughout the experiment to prevent participants from hearing the vibration. Data analyses were conducted using MATLAB 2017b (The MathWorks, Inc.) and the Palamedes toolbox (Prins & Kingdom, 2018).

Stimuli

Stimulation consisted of an ongoing constant vibration that lasted 1.6 sec. The detection target was embedded within the ongoing stimulation and consisted of a brief (0.04-sec) decrement in intensity (Figure 1A). We use arbitrary units (AU) to describe the intensity of the vibration and ΔAU to describe the decrement, where Δ = constant intensity − target intensity. The intensity of the ongoing constant vibration was 160 AU, and that of the decrements (i.e., the targets) was parametrically varied, ranging from Δ20 to Δ140 AU, in steps of 20. This resulted in seven target intensity levels: Δ20, Δ40, Δ60, Δ80, Δ100, Δ120, and Δ140—from difficult to easily detectable targets, respectively. In certain cases, two additional intensities were used (Δ10 and Δ150), but as all participants did not have these extreme values, they were excluded from analyses (see Procedure).

Target onset could either be temporally predictable or randomly presented within the vibrotactile stimulation. In the Predictable condition, the target occurred at 0.8 sec within the 1.6-sec-long stimulation. In the Random condition, target onset was randomized from 0.4 to 1.2 sec following the onset of the vibrotactile stimulation (Figure 1A).

Task

Participants were instructed to focus on a fixation cross while attending to their dominant hand (the stimulation site). In each trial, an ongoing vibrotactile stimulation was delivered to participants' index finger, at the end of which a response screen prompted them to indicate whether they had felt the embedded target or not via a key-press. They were instructed that there would be easy and hard trials, as well as trials without a target at all (catch trials).

Participants pressed the "d" key for "yes" and the "a" key for "no." To keep false alarm rates to a minimum, we instructed participants to be conservative: to only answer "yes" when they were "quite sure" that they had felt the target, and to otherwise answer "no."

The Predictable and Random conditions were blocked and counterbalanced across participants. Within each of these conditions, target intensities were blocked. Each intensity block included 20 trials with a target and 20 trials with no target (i.e., 50% catch trials per target intensity). The order of target-present and catch trials was randomized. The blocked target intensities were presented in randomized order, except the first, which was always the easiest (i.e., Δ140, or the second easiest, for those few participants who also performed Δ150; see Procedure).

Procedure

After signing an informed consent form, participants were seated in front of a computer monitor, 75 cm from the screen, with their dominant arm positioned on the chair's armrest, palm-down. Their wrist was supported but the hand itself made no contact with the armrest (i.e., was hanging off the armrest). The vibrotactile stimulator was secured to their dominant index fingertip with a customized, elastic bandage. Participants were instructed to keep their arm still, palm-down, with their fingers relaxed and hanging off the armrest, as positioned by the experimenter. To ensure that no changes occurred, neither to the experimental setup nor to the participants' arm position, the participants were continuously monitored by the experimenter through a live-feed camera. Their nondominant hand rested on the keyboard (for response). The computer monitor showed a white cross centrally positioned against a black background that served as a fixation cross throughout the experiment, and the response options appeared on either side of it, corresponding to their positions on the keyboard (i.e., "no" on the left side of the cross and "yes" on the right).

After instructions were given, participants underwent a practice phase, consisting of 32 trials. Here, participants were familiarized with the ongoing, constant stimulation, as well as with target-present trials. Then, they completed a short practice block (30 total trials: 5 trials for each of the three easiest intensities and 15 catch trials). Practice was repeated if participants scored either <80% hit rate or >20% false alarm rate. All participants met this criterion after a maximum of three repetitions. The experimenter remained present in the room during the practice phase.

After completing the practice, participants wore headphones and listened to white noise while they performed the experiment. All participants began with an easy target intensity (Δ140), after which performance was assessed. If they met the criterion (as in the training, i.e., ≥80% hit rate and ≤20% false alarm rate), they continued on to the rest of the experiment. Otherwise, participants repeated this block to ensure that they understood the task. If they still failed to meet the criterion, they were given an even easier block (Δ150 target intensity), after which performance was reassessed. If participants still failed to meet the criterion, they were excused from the experiment. Otherwise, they continued on to the rest of the experimental blocks.

The interval between trials was set to 1 sec, with a 0.25-sec jitter (1–1.25 sec). There were short breaks every 100 trials and a longer break between the two blocked timing conditions (i.e., Predictable and Random). Before starting the second condition, participants performed another practice phase, which they were told was just standard protocol after a long(er) break. The practice for both conditions was identical except for the temporal properties of the detection target: The possible target onset times corresponded to the condition (i.e., Predictable or Random) being performed. At the end of the experiment, participants were either paid for their time or granted class credit.

Experiment 2

We replicated the same experiment in the auditory modality. The same apparatus was used, except that the experiment was run with the Psychtoolbox (Brainard, 1997) extensions of MATLAB 2014b (The MathWorks, Inc.). The structure of the task was identical (see Task of Experiment 1). For differences between experiments, see below.

Participants

We pre-specified a sample size of 20 participants based on previous psychophysical and temporal expectation studies. Twenty healthy individuals took part in a psychophysical experiment for payment or class credit. Three participants were excluded because of lack of dynamic range, for example, extremely poor or exceedingly good performance across the target intensities (mean detection rates: 7.5%, 95.9%, and 98.8%—floor and ceiling effects across the experiment). Two additional participants were considered poor performers, as their maximum detection rates were barely at 50% (mean detection rates: 16.3% and 26.3%). These two participants were included in the average accuracy analysis because they exhibited monotonically increasing performance across the target intensities but were excluded from the analysis that focused on 50% threshold performance. The mean performance analysis is thus presented for 17 participants (ages 20–28 years, average = 23.9 years; 10 women; 16 right-handed), but the analysis reporting estimations of the 50% threshold is presented for 15 participants. Importantly, including these two participants in this analysis does not alter the main result (mean 50% threshold, Predictable minus Random = −0.016 ΔAU [−0.030, −0.0019], p = .026). Similarly to the main report, here too there was no difference in slopes (mean difference in slopes = −0.086 [−0.19, 0.02], p = .11) or false alarms (mean difference in false alarms = 0.18% [−0.85, 1.2], p = .71) between the Predictable and Random timing conditions. Participants signed a consent form before experimentation, and the study was approved by the institutional review board of human experimentation at The Hebrew University of Jerusalem.

Stimuli

Stimulation consisted of an ongoing (1.6-sec) segment of Gaussian white noise presented binaurally through Sennheiser headphones, with a brief (0.04-sec) intensity decrement, which was the detection target (Figure 1B). We again use AU to describe the intensity of the white noise and ΔAU to describe the decrement, where Δ is denoted by a value ranging from 1 to 8 and represents the intensity of the decrements (i.e., the targets), which were parametrically varied (see Procedure). The volume was kept constant across participants, at 25% of the maximum PC value. All noise stimuli were created offline, with a 0.02-sec raised cosine ramp at onset and offset. We used eight target intensities, here tailored to each participant's threshold of performance by administering a short block in the beginning of the experiment (see Procedure of Experiment 2) utilizing the method of constant stimuli. Again, as in Experiment 1, target onset could either be temporally predictable or randomly presented within the auditory stimulation. In the Predictable condition, the target occurred at 0.8 sec within the 1.6-sec-long stimulation. In the Random condition, target onset was randomized from 0.4 to 1.2 sec following the onset of the auditory stimulation, creating a possible target-onset window of 0.8 sec (Figure 1B).

Procedure

After signing an informed consent form, participants were seated in front of a computer monitor, 70 cm from the screen. The computer monitor showed a black cross centrally positioned against a gray background that served as a fixation cross throughout the experiment, and the response options appeared on either side of it, corresponding to their positions on the keyboard (i.e., "no" on the left side of the cross and "yes" on the right).

After instructions were given, participants underwent a familiarization phase (two trials, a segment of white noise without and then with a target), and then, as in Experiment 1, they underwent a practice phase, consisting of 12 total trials (six trials of very easy stimulus intensity and six catch trials). Then, participants performed a short block with a wide range of target intensities to determine a suitable dynamic range based on their performance (1 trial per intensity, 15 intensities logarithmically equally spaced between a 0% and 90% amplitude decrement of the ongoing white noise). The range of stimulus intensities for the actual experiment were chosen by taking the four intensities below and above the "rough" detection threshold observed here for each participant. This range was used for both timing conditions and so was only performed once throughout the experiment. Once these steps were completed, they continued on to the rest of the experimental block.

The interval between trials was set to 1 sec, with a 0.25-sec jitter (1–1.25 sec). There were short breaks every 100 trials and a longer break between the two blocked conditions (i.e., Predictable and Random). Before starting the second condition, participants performed another practice phase. The practice for each condition was identical except for the temporal properties of the detection target: The possible target onset times corresponded to the condition (i.e., Predictable or Random) being performed. At the end of the experiment, participants were either paid for their time or granted class credit.

General

Analyses

For each participant included in the analysis, we estimated the percentage of hits, misses, correct rejections, and false alarms for each condition (Predictable, Random) separately.

For all main analyses, we used a two-tailed percentile bootstrap procedure for dependent groups, with 10,000 samples with replacement (Wilcox, 2012; Efron & Tibshirani, 1993). We compared mean detection rates between temporal expectation conditions (Predictable vs. Random; target intensities, collapsed) by calculating percentile confidence intervals around the mean difference between the two timing conditions (Predictable minus Random). First, we sampled participants with replacement, keeping their corresponding mean detection rates (i.e., averaged across target intensity levels) in the Predictable and Random conditions. We then calculated the mean difference between conditions (Predictable minus Random) across all (sampled) participants. We performed these two steps 10,000 times, and each time saved the mean difference between conditions. Then, we sorted the bootstrapped mean, and used the 2.5 and 97.5 percentiles to form the boundaries of the 95% bootstrap confidence intervals (for an alpha, $\alpha = .05$). To calculate whether the detection rates in the Predictable and Random conditions differed from each other, we estimated the overlap of the bootstrapped distribution with zero (i.e., the null hypothesis that there is no difference in detection rates between the two timing conditions) in the following manner: p value = (one minus the percentage of bootstrap values above [or below] zero, multiplied by two [for a two-tailed test]).

To estimate psychometric functions, the responses (hit rates or percent detection) for each participant were modeled by fitting logistic and cumulative normal functions for Experiments 1 and 2, respectively, using a maximum-likelihood procedure for each condition (Predictable, Random) and experiment (Tactile, Auditory; Palamedes toolbox; Prins & Kingdom, 2018). We then calculated the 50% threshold of performance, as well as the slope of the psychometric curve, for each condition separately. Both threshold (α) and slope (β) parameters were allowed to vary freely, whereas guess ($\gamma = 0$) and lapse ($\lambda = 0.01$) rates were fixed for all participants.

To make sure that there was no inherent advantage or disadvantage to detecting targets appearing in the middle of a trial (i.e., that any differences between conditions were not merely driven by performance to targets appearing in the central time window of the Random timing condition relative to the earlier and later times of possible target onset), we compared participants' detection rates to targets appearing in the middle of the trial to their detection rates to targets appearing in early and late times in the trial. To this end, we assigned trials to one of three time bins (early, 400–749 msec; middle, 750–850 msec; and late, 851–1200 msec) according to target onset, collapsed early and late time bins, and compared performance between middle versus early and late bins. Additionally, we compared performance in the central time period of the Random timing condition (750–850 msec) to performance in the Predictable timing condition (800 msec). By design, there are far fewer trials in the central time bin, within the random timing condition. Therefore, the Predictable timing condition was subsampled on a single-subject basis to match the number of trials in the Random timing condition. This subsampling was performed 1000 times, after which differences in detection performance between the two timing conditions were calculated (Predictable minus Random; i.e., 1000 difference values per participant). The percentile confidence intervals around the mean difference between the two timing conditions (Predictable minus Random) were calculated, and the overlap between the distribution of mean differences with zero were calculated using the same procedure as described above.

An analysis comparing RTs for detected targets shows no effect of target predictability (tactile: mean RT across the entire experiment = 0.65 sec; difference between conditions, Predictable minus Random = −0.072 sec [−0.15, 0.021], $p = .12$; auditory: mean RT across the entire experiment = 0.51 sec; difference between conditions, Predictable minus Random = −0.022 sec [−0.085, 0.053], $p = .51$). This is expected since responses were delivered after the termination of the ongoing stimulation, following a response prompt. In addition, this is also consistent with instructions requesting participants to prioritize accuracy in their performance.

Last, we performed an SDT analysis between the two timing conditions. This analysis entailed the comparison of target intensity levels for a given d' or criterion value (separately). First, we computed the d' and criterion in the Predictable timing condition, at the 50% threshold

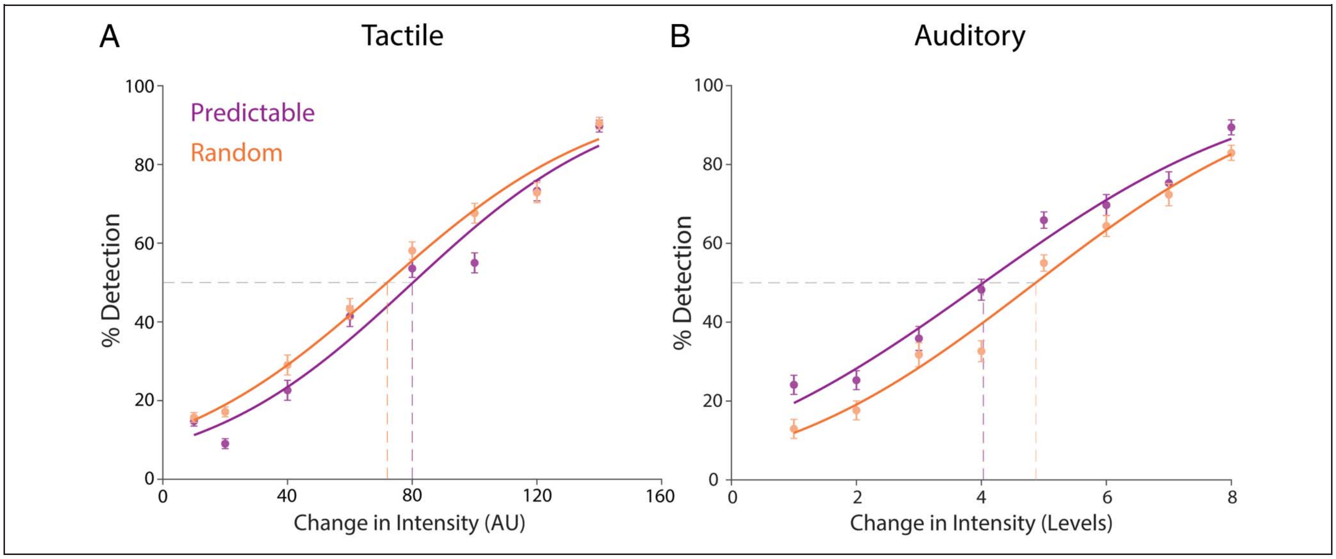

Figure 2. Detection performance. Mean psychometric functions in the Predictable and Random timing conditions for Experiments 1 (A) and 2 (B). In Experiment 1 (tactile; A), participants ($n = 21$) were generally better at detecting tactile targets when they appeared at random times within the ongoing vibrotactile stimulation, compared with when presented temporally predictable targets. The opposite was observed in Experiment 2 (auditory; B), in which participants ($n = 17$) were generally better at detecting predictable auditory targets, compared with those appearing randomly within the ongoing white noise.

of detection performance. We then compared the intensity level required to achieve that given d' and criterion in the Random condition. Thus, we capture the amount of signal required under the different timing conditions, which yields a given SDT value (d' or criterion, separately). These target intensity levels were then subjected to a two-tailed percentile bootstrap procedure to determine whether sensitivity and response

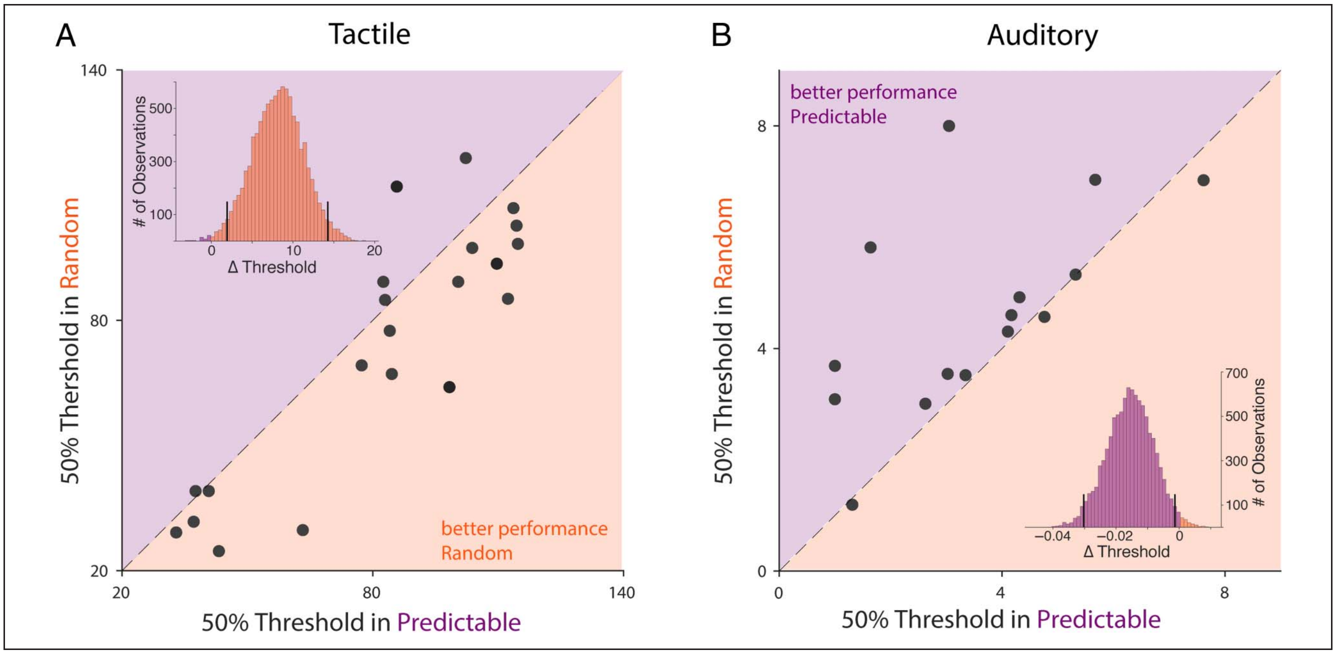

Figure 3. Individual threshold performance. Scatter plot shows the 50% thresholds for individual participants (single points) in the Predictable and Random timing conditions for each experiment (tactile, A; auditory, B). (A) In Experiment 1, nearly all participants exhibited lower thresholds in the Random timing condition (most participants to the right of the identity line). A percentile-bootstrap of individual subject threshold differences ($n = 10{,}000$ samples; see inset) yields a distribution significantly greater than 0 (i.e., consistently lower thresholds in the Random timing condition; mean difference between 50% thresholds, Predictable minus Random = 8.18 ΔAU [1.94, 14.41], $p = .011$). Black vertical bars denote the 2.5 and 97.5 percentiles of the 95% confidence intervals. (B) In Experiment 2, participants showed the opposite. Nearly all participants exhibited better performance in the Predictable timing condition (all but one participant to the left of the identity line). A percentile-bootstrap of individual subject threshold differences (see inset) yields a distribution significantly lower than 0 (i.e., consistently lower thresholds in the Predictable timing condition; mean difference between 50% thresholds, Predictable minus Random = −0.020 ΔAU [−0.034, −0.007], $p = .001$). Auditory axes denote threshold level (1–8), because auditory range was tailored to individuals and thus differed across participants.

bias were modulated by temporal expectation (see Figure 4).

RESULTS

Experiment 1

Figure 2A shows the mean psychometric functions in the Predictable and Random timing conditions. As per experimental design, participants' performance increased as a function of increasing target intensities, from nearly no target detection at the hardest intensity levels to almost perfect target detection at the easiest intensity levels. To examine the effects of temporal prediction on target detection, we first compared overall mean detection rates between the two timing conditions (Predictable vs. Random) and subsequently the 50% thresholds of each timing condition.

For all main analyses, we used a two-tailed percentile bootstrap procedure for dependent groups, with 10,000 samples with replacement. We compared overall mean detection rates between the two timing conditions (Predictable vs. Random; target intensities, collapsed) by calculating percentile confidence intervals around their difference (see Methods, section General, Analyses). Square brackets indicate the boundaries of the 95% confidence intervals constructed from this analysis.

Contrary to other sensory modalities, in Experiment 1 participants generally exhibited higher detection rates for tactile targets appearing at random (within the 0.4–1.2 sec range), rather than at predictable (0.8 sec), times (mean detection rate across all target intensities, Predictable minus Random = −4.83% [−8.19, −1.53], p = .004).

In addition, we compared target intensities corresponding to the 50% detection rate in each timing condition, as estimated from individual participants' psychometric fits. Here too, participants exhibited lower detection thresholds for the Random timing condition (mean 50% threshold, Predictable minus Random = 8.18 ΔAU [1.94, 14.41], p = .011). Nearly all participants showed this pattern (see Figure 3A). There was no difference in slopes (mean difference in slopes = 0.002 [−0.096, 0.097], p = .95) or false alarms (8.8 ± 8.5% mean false alarm rate across the entire experiment; mean difference in false alarms = −0.85% [−2.3, 0.6], p = .25) between the Predictable and Random timing conditions.

Importantly, the observed differences in detection rates were not merely driven by suboptimal performance in the central time window of a trial (i.e., around 0.8 sec, the time of target onset in the Predictable timing condition). We compared performance between trials in which targets appeared in central versus early and late time bins and observed no difference in detection rates between bins (mean detection rate, Early/Late minus Central time bins = −3.69% [−8.29, 0.64], p = .1). Additionally, we compared performance between trials in which targets

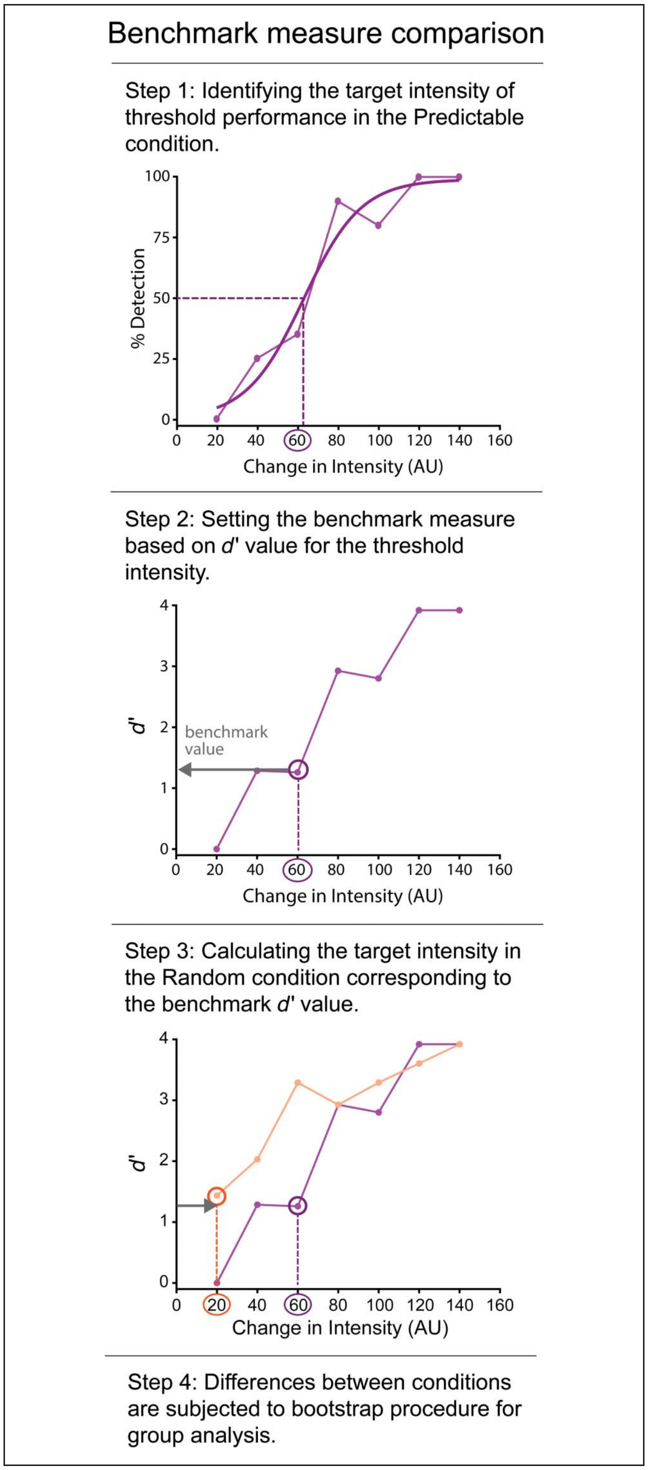

Figure 4. SDT analysis pipeline. To compare d' and criterion between timing conditions, we first computed the 50% threshold of detection performance in the Predictable condition (Step 1). Then, we computed d' and criterion (separately) at this target intensity level (Step 2). Last, we determined the target intensity level in the other timing condition (i.e., Random timing condition) for this benchmark d' and criterion value (separately for each measure; Step 3). The SDT analysis thus entailed the comparison of target intensity levels for a given d' or criterion value. For a given d' value, a more difficult target intensity level indicates that participants were more sensitive to the signal change in this condition, and vice versa.

appeared in central time bins of the Random timing condition with a subsample of trials from the Predictable timing condition, to compare detection performance at the same absolute time (with respect to trial onset), but with different temporal expectation. Participants exhibited higher detection performance in the Random timing condition compared with the Predictable (mean difference in detection, Predictable minus Random = −10.64% [−14.70 −6.62], $p < .001$).

Last, we conducted an SDT analysis between timing conditions to assess whether sensitivity (d') and response bias (criterion) were also modulated by temporal expectation. Participants exhibited greater sensitivity in the Random timing condition: For a given d' value, the Random condition required a more difficult (i.e., weaker) target intensity level, indicating that participants were more sensitive to the signal change in this condition (Predictable minus Random = 19.05 ΔAU [0.48, 38.09], $p = .044$). Similarly, participants exhibited a lower criterion (less conservative response pattern) in the Random timing condition compared with the Predictable condition (Predictable minus Random = 21.9 ΔAU [8.57, 36.67], $p = .0014$). In other words, participants needed easier targets (higher target intensity levels; specifically, ~20 ΔAU, or one target intensity level easier) in the Predictable condition compared with the Random condition to exhibit similar perceptual sensitivity levels or a similar response bias (see Figures 4 and 5).

Experiment 2

In our first experiment, detection targets were embedded within an ongoing vibrotactile stimulation that lasted 1.6 sec. This experimental approach is rather different from those used in previous studies, which typically employed short, near-threshold amplitudes presented within a silent interval. Thus, to rule out any peculiarities from our stimulus and experimental design, we ran an additional experiment, Experiment 2, identical in structure, but in the auditory modality. In Experiment 2 and in line with previous work, participants exhibited higher detection rates for auditory targets appearing at predictable, rather than random, times (mean detection rate, Predictable minus Random = 8.01% [3.01, 13.68], $p = .001$). Figure 2B shows the mean psychometric functions in the Predictable and Random conditions. As expected and again as per experimental design, performance increased as a function of target intensity in both conditions. As in Experiment 1, we then ran an additional analysis, comparing target intensities corresponding to the 50% detection rate in each condition. This analysis confirmed the observation that participants generally

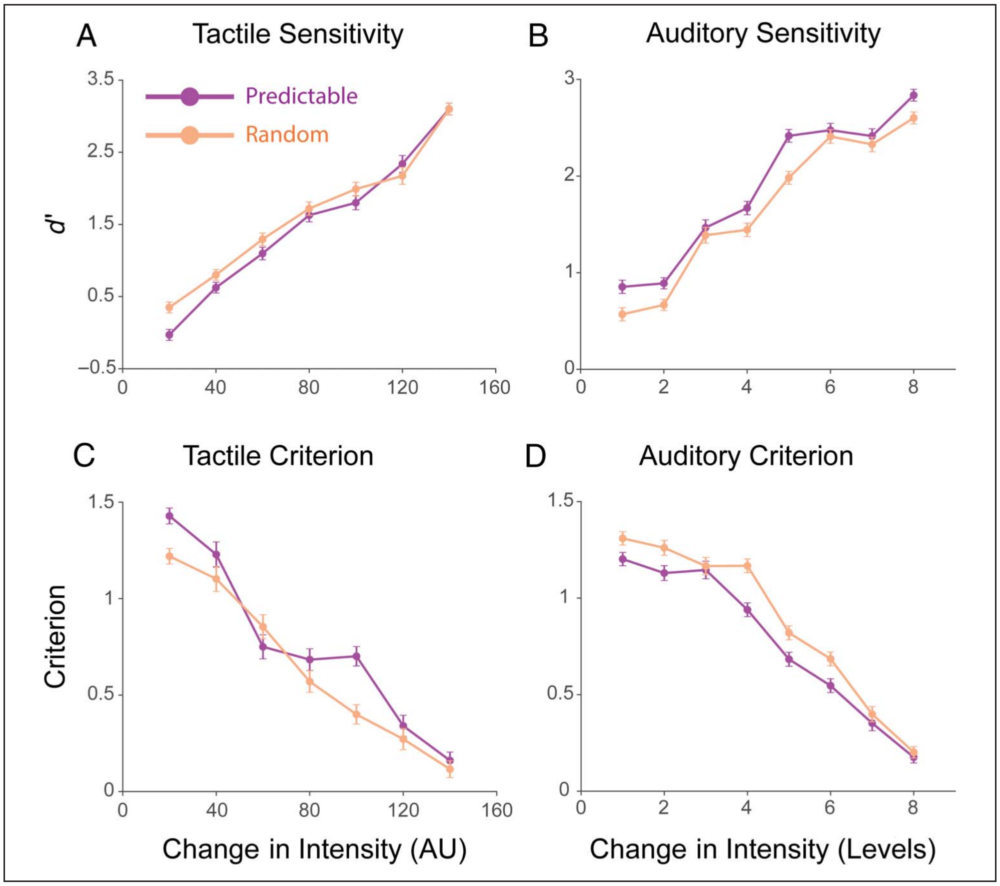

Figure 5. Sensitivity and response bias. Mean d' and criterion across target intensity levels in the Predictable and Random timing conditions for Experiments 1 and 2. In Experiment 1 (tactile), participants exhibited greater sensitivity (A) to targets in the Random timing condition (Predictable minus Random = 19.05 ΔAU [0.48, 38.09], $p = .044$) and a less conservative response pattern (C) in the Random timing condition (Predictable minus Random = 21.9 ΔAU [8.57, 36.67], $p = .0014$). The opposite was observed in Experiment 2 (auditory), in which participants were more sensitive (B) to targets in the Predictable timing condition (Predictable minus Random = −0.038 ΔAU [−0.067, −0.013], $p = .003$). SDT analysis entailed the comparison of target intensity levels for a benchmark d' or criterion value (separately; see Figure 4).

displayed lower thresholds in the Predictable versus Random condition (mean 50% threshold, Predictable minus Random = −0.020 ΔAU [−0.034, −0.007], p = .001). Again, nearly all participants showed this pattern (see Figure 3B). There was no difference in slopes (mean difference in slopes = −0.098 [−0.2135, 0.0182], p = .1) or false alarms (2.0 ± 2.7% mean false alarm rate across the entire experiment; mean difference in false alarms = 0.04% [−1.1, 1.2], p = .9) between the Predictable and Random timing conditions.

As in Experiment 1, an analysis between trials in which the target appeared in central versus early and late time bins revealed no difference in performance, indicating that the observed threshold differences cannot be attributed merely to increased performance in the central time bin (mean difference, Early/Late minus Central bins = 3.3% [−4.6, 11.3], p = .4). Additionally, we compared performance between trials in which targets appeared in central time bins of the Random timing condition with a subsample of trials from the Predictable timing condition to compare detection performance at the same absolute time (with respect to trial onset), but with different temporal expectancy. Participants exhibited higher detection performance in the Predictable timing condition compared with the Random timing condition (mean difference in detection, Predictable minus Random = 9.81% [4.99, 14.77], p < .001).

Last, we conducted an SDT analysis between timing conditions to assess whether sensitivity (d') and response bias (criterion) were modulated by temporal expectation. Consistent with the observed increase in detection performance in the Predictable timing condition, participants also exhibited a higher sensitivity in the Predictable condition. For a given d' value, the Random condition required an easier (i.e., stronger) target intensity level, indicating that participants were less sensitive to the signal change in this condition (Predictable minus Random = −0.038 ΔAU [−0.067, −0.013], p = .003). Participants did not exhibit a lower criterion (more liberal response bias) in the Predictable timing condition compared with the Random condition (for a given criterion value, mean difference in target intensity levels, Predictable minus Random = −0.017 ΔAU [−0.043, 0.0063], p = .17; see Figures 4 and 5).

DISCUSSION

In this study, we investigated whether implicit temporal expectations enhance detection in the tactile modality. To this end, we embedded a brief target—an intensity decrement—in an ongoing vibration, which participants had to detect. We show that, contrary to the role of temporal expectations in other sensory modalities, implicit temporal predictions do not have a facilitative effect on tactile detection, but rather deter performance, as indexed by increased detection thresholds in the Predictable versus Random condition. In contrast, a control experiment showed that participants more readily detected an auditory target if presented at a predictable time point within the trial.

Our results present a puzzle within the context of perceptual systems, given previous lines of work in vision and audition: Implicit temporal expectations have a detrimental effect on the somatosensory system, leading to better performance in conditions of temporal uncertainty. What key differences between tactile and the visual or auditory modalities might account for this discrepancy? Contrary to vision and audition, somatosensation is coupled to the motor system, in that the intensity of sensation is often determined by the force exerted by our motor system. Although other senses are also, to a certain degree, governed and affected by the motor system (Wurtz, McAlonan, Cavanaugh, & Berman, 2011), the somatosensory system is a proximal sense in that the intensity of static objects is entirely dependent on motor action. This means that, in addition to the engaged sensory system, the motor systems also bear information about the intensity of a somatosensory stimulation. The (somato) sensory consequences of our actions are normally highly predictable, making (spatial and temporal) anticipation an inherent feature of touch. It is possible that predictability weighs in on somatosensation differently from vision and audition due to its active nature, and as a result, it is most efficiently tuned to tracking changes in our environment or unexpected (somato)sensory consequences. Accordingly, in the context of self-generated actions, previous research has described a phenomenon called tactile suppression.

Tactile suppression is a prediction-based sensory modulation. It is typically observed following self-generated movement and manifests as a (somato)sensory attenuation to the body part being moved or to which a probe stimulus is being directed. In such cases, the sensations evoked by self-generated forces are perceived as weaker than of those caused by externally generated forces of the same magnitude (Juravle, Binsted, & Spence, 2017; Chapman, Bushnell, Miron, Duncan, & Lund, 1987). This phenomenon is thought to originate from sensory predictions produced in conjunction with the motor command (i.e., the "efference copy"; Shergill, Bays, Frith, & Wolpert, 2003; Wolpert, Ghahramani, & Jordan, 1995) and is considered key for distinguishing between self- and externally generated forces. The cognitive system is thus desensitized to sensations that result from our own motor actions (that are predictive in time and space) and is sensitized toward sensations we cannot predict.

The sensory prediction of self-generated forces has been explored in work showing that tactile attenuation is proportional to temporal and spatial prediction errors. Specifically, greater delays and spatial perturbations to the intended stimulation resulted in similar levels of sensory suppression as produced by externally generated (e.g., robot-produced) forces, which cannot be predicted (Blakemore, Frith, & Wolpert, 1999). Blakemore et al.

(1999) showed that, as a tactile stimulus diverged from participants' motor program prediction, either temporally or spatially, participants reported stronger somatosentation (i.e., higher rates of tickling). This study highlights the properties of prediction (space and time) that are pivotal in producing sensory attenuation, within the context of self-generated actions.

In our study, the prediction did not involve motor planning; nonetheless, a sensory prediction was formed in the Predictable condition. The effects of this prediction are evident in the difference in performance between the Predictable and Random conditions and point to a similar mechanism: attenuation of sensation in light of sensory prediction. As previously shown within the context of tactile suppression (Juravle & Spence, 2011), we also observed a deterioration in tactile sensitivity in the Predictable timing condition, in which participants consistently needed a higher target intensity level (i.e., an easier target) for a given d' value, as compared with the Random timing condition. This decrease in perceptual sensitivity was accompanied by a significant conservative shift in participants' criterion (i.e., more likely to respond, "no" in the Predictable condition to tactile target detection). In the auditory modality, on the other hand, participants exhibited the opposite pattern—in the Predictable timing condition, they exhibited a given d' value with a more difficult target, compared with the Random timing condition. Our data thus highlight the role of sensory predictions in producing somatosensory attenuation and suggest that tactile suppression generalizes beyond the case of self-generated action to the case of sensory predictions based on stimulus history. In our study, an implicit temporal prediction was embedded in an externally presented stimulus. This prediction was presented to an otherwise passive participant and led to attenuation in somatosensation, akin to the well-studied sensory prediction due to self-generated action.

To summarize, we here demonstrate the impact of implicit temporal prediction on participants' ability to detect an upcoming target. We suggest that the decrement in tactile performance might result from sensory suppression driven by the temporal and spatial certainty linked to the putative "efference copy." Importantly, we provide evidence that temporal anticipation has a divergent effect in different sensory systems. Intuitively, one would assume that temporal structure would impact performance equivalently over all sensory systems. We demonstrate a clear counterexample to this intuition. In the tactile domain, temporal uncertainty, rather than certainty, is met with a further optimized system for the detection of brief targets.

Acknowledgments

This work was supported by funds from the James McDonnell Scholar Award for Understanding Human Cognition, the National Israeli Psychobiology Institute, and the Israel Science Foundation (all awarded to A. N. L.). As a library fellow, A. N. L. would like to thank the Van Leer Jerusalem Institute for providing the space to think and write. S. P. is supported by the Jerusalem Brain Community. The authors would like to thank Dr. David Carmel and other members of the brain and attention time lab (landaulab.com) for insightful comments on the work, as well as Lorenzo Pisoni, Niv Pagir, and Yaniv Abir for their technical contributions to the experimental setup.

Conceptualization, F. K., S. P., G. M., and A. N. L.; methodology, F. K., S. P., G. M., and A. N. L.; software, F. K. and S. P.; investigation, G. M. and S. P.; formal analysis, F. K. and A. N. L.; writing—original draft, F. K.; writing—review and editing, F. K., A. N. L., S. P., and G. M.; visualization, F. K., S. P., and A. N. L.; supervision and funding acquisition, A. N. L.

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