Title: **Reciprocal interactions between audition and touch in flutter frequency perception**

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Abstract

In both audition and touch, sensory cues comprising repeating events are perceived either as a continuous signal or as a stream of temporally discrete events (flutter), depending on the events' repetition rate. At high repetition rates (>100Hz), auditory and tactile cues interact reciprocally in pitch processing: The frequency of a cue experienced in one modality systematically biases the perceived frequency of a cue experienced in the other modality. Here, we tested whether audition and touch also interact in the processing of low frequency stimulation. We also tested whether multisensory interactions occurred if the stimulation in one modality comprised click trains and the stimulation in the other modality comprised amplitude modulated signals. We found that auditory cues bias touch and tactile cues bias audition on a flutter discrimination task. Moreover, we observed similar interaction patterns regardless of stimulus type and whether the same stimulus types were experienced by both senses. Combined with earlier studies, our results suggest that the nervous system extracts and combines temporal rate information from multisensory environmental signals, regardless of stimulus type, in both the low- and high temporal frequency domains. This function likely reflects the importance of temporal frequency as a fundamental feature of our multisensory experience.

Introduction

Environmental oscillations signal information about objects in our surroundings and our interactions with those objects. Although the oscillations we encounter by audition and touch span a wide range of temporal frequencies, the perception of sensory cues comprising repeating events in both sensory modalities can be organized into two domains depending on the repetition rate of the events. At low repetition rates, signals are perceived as a stream of temporally discrete events. At higher repetition rates (>50Hz), signals are perceived as a single continuous signal. These two domains are categorized as flutter and vibration in touch, and processing in these domains is mediated by distinct neural populations in the peripheral and central somatosensory systems[1,2]. Auditory perception can be similarly categorized into these two domains, with acoustic flutter perceived at rates near or below the lower limit for perceiving pitch[3,4]. Acoustic flutter and pitch also appear to have distinct neural representations[5].

Audition and touch clearly interact in the perception of high frequency stimulation[6]. Auditory signals influence the detection[7,8] and perception of vibrations[9]. Tactile cues can also bias auditory perception[10]. These bidirectional interactions in frequency perception may reflect the processing of multimodal neural circuits that represent frequency information signaled by both senses, as suggested by crossmodal adaptation and modeling results[11]. Indeed, a number of brain regions respond to both auditory and tactile stimulation[12–16] and causal manipulation of some regions modulates both auditory and tactile perception[17–20]. Thus, shared or interactive neural systems likely support the integration of auditory and tactile signals occupying the high frequency domain.

Although analogous neural coding schemes are used to represent auditory and tactile flutter[5,21] and some cortical neurons explicitly signal flutter frequency in both modalities[22,23], few studies have characterized perceptual interactions between audition and touch in the flutter domain[24]. Here, we tested the influences of auditory signals on tactile flutter perception and of tactile signals on auditory flutter perception. We additionally tested whether interactions between audition and touch depended on the exact composition of the flutter stimulus. Specifically, do flutter stimuli comprising click trains and amplitude modulated (AM) signals participate similarly in multisensory interactions? We also investigated whether the auditory and tactile flutter signals must be of matching stimulus types (i.e., both click trains or AM signals) in order for the two senses to interact. Because click trains and AM stimuli may be represented by distinct neural populations[25–27], establishing whether audio-tactile flutter interactions are invariant to stimulus type would provide insights into what neural populations contribute to multisensory interactions in flutter perception.

Results

Experiment 1: Effects of auditory distractors on tactile flutter discrimination

Participants performed a flutter discrimination task with tactile click trains (CT_T) in the absence of auditory distraction or while they heard auditory click trains (CT_A) or amplitude-modulated (AM_A) flutter signals. CT_A and AM_A distractors could be higher or lower in frequency compared to the tactile standard stimulus. While participants reliably performed the tactile discrimination task in the baseline and distractor conditions (mean psychometric function $r^2 \pm SD = 0.98 \pm 0.01$), performance patterns changed systematically with both CT_A distractors (Fig. 1a) and AM_A distractors (Fig. 1b). A one-way repeated-measures ANOVA conducted on estimates of the point of subjective equality (PSE) indicated that auditory distractors significantly biased tactile performance ($F(4,36) = 44.50$, p = 1.8579e-13, $\eta_p^2 = 0.83$) (Fig. 1c). Although baseline performance was unbiased ($PSE_{Base} \pm$ s.e.m.: 26.12 ± 0.15Hz), a two-way rmANOVA conducted on PSE estimates in the distractor conditions (Fig. 1d) revealed that the perception of the 26-Hz tactile standard was biased toward the frequency of the auditory distractors (frequency main effect: $F(1,9) = 182.58$, p = 2.7847e-07, $\eta_p^2 = 0.95$). The main effect of distractor type did not achieve significance ($F(1,9) = 1.00$, p = 0.34, $\eta_p^2 = 0.10$), but there was a significant frequency x type interaction ($F(1,9)= 11.47$, p= 0.008, $\eta_p^2= 0.56$) which suggests that distractor effects on PSE may be more pronounced with AM_A distractors. To better compare the magnitude of distractor effects, we performed a two-way rmANOVA on the absolute PSE differences between the baseline and distractor conditions. This analysis revealed only a significant main effect of frequency ($F(1,9) = 39.15$, p = 0.0001, $\eta_p^2 = 0.81$), but no significant effect of type ($F(1,9) = 4.76$, p = 0.06, $\eta_p^2 = 0.34$) nor interaction effects ($F(1,9) = 0.60$, p = 0.46, $\eta_p^2 = 0.06$). These results indicate that CT_A and AM_A distractors exerted comparable attractive biasing effects on judgments of tactile click trains in a manner that depended on distractor frequency.

A one-way rmANOVA conducted on estimates of the just-noticeable difference (JND) indicated that auditory distractors significantly impaired tactile sensitivity to flutter frequency differences ($F(4,36) = 4.37$, p = 0.005, $\eta_p^2 = 0.33$) (Fig. 1e,f). To test whether auditory distractor effects on JND depended on distractor conditions, we conducted a two-way rmANOVA which revealed no significant main effects nor interactions (frequency main effect: $F(1,9) = 3.49$, p = 0.09, $\eta_p^2 = 0.28$; type main effect: $F(1,9) = 0.23$, p = 0.64, $\eta_p^2 = 0.03$; interaction effect: $F(1,9) = 0.26$, p = 0.62, $\eta_p^2 = 0.03$). These results indicate that auditory distractors impaired tactile sensitivity to flutter frequency in a non-specific manner.

Experiment 2: Effects of tactile distractors on auditory flutter discrimination

A separate group of participants performed a flutter discrimination task with auditory click trains (CT_A) in the absence of tactile distraction or while they felt tactile click trains (CT_T) or amplitude-modulated (AM_T) flutter signals. While participants reliably performed the tactile discrimination task in the baseline and distractor conditions (mean psychometric function $r^2 \pm$ SD = 0.99 ± 0.01), performance patterns changed systematically with both CT_T distractors (Fig. 2a) and AM_T distractors (Fig. 2b). A one-way rmANOVA conducted on PSE estimates indicated that tactile distractors significantly biased auditory performance ($F(4,36)$ = 7.71, p = 0.0001, η_p^2 = 0.46) (Fig. 2c). A two-way rmANOVA conducted on PSE estimates revealed a significant main effect of distractor frequency ($F(1,9)$ = 14.43, p = 0.004, η_p^2 = 0.62), but the main effect of distractor type and the frequency x type interaction failed to achieve significance (type main effect: $F(1,9)$ = 1.78, p = 0.21, η_p^2 = 0.16; interaction effect: $F(1,9)$ = 0.03, p = 0.87, η_p^2 = 0.003). While the main effect of frequency can be appreciated in the attractive influences of the 16- and 36-Hz tactile distractors on the perceived frequency of the 26-Hz auditory flutter stimulus (Fig. 2c,d), this result does not indicate whether the magnitude of the bias effects differed according to distractor frequency. A two-way rmANOVA conducted on the absolute PSE differences between the baseline and distractor conditions yielded no significant main nor interaction effects (frequency main effect: $F(1,9)$ = 0.03, p = 0.86, η_p^2 = 0.004; type main effect: $F(1,9)$ = 0.29, p = 0.60, η_p^2 = 0.03; interaction effect: $F(1,9)$ = 3.50, p = 0.09, η_p^2 = 0.28). These results indicate that CT_T and AM_T distractors exerted similar attractive biasing effects on judgments of auditory click trains in a manner that depended on distractor frequency.

A one-way rmANOVA conducted on JND estimates (Fig. 2e,f) indicated tactile distractors did not significantly modulate auditory sensitivity to flutter frequency differences ($F(4,36)$ = 1.74, p = 0.16, η_p^2 = 0.16).

Comparison between experiments 1 and 2

Flutter discrimination performance by touch and audition was biased by attractive influences of distractors presented in the other modality. To compare the biasing effects in experiment 1 (auditory distractors on tactile flutter discrimination) and experiment 2 (tactile distractors on auditory flutter discrimination), we performed a mixed-design ANOVA on the PSE estimates with distractor type (2 levels: CT, AM), distractor frequency (2 levels: 16Hz vs 36Hz) as within-subjects factors and experiment (which was a proxy for the test and distractor modality pairings in each experiment; 2 levels: tactile-auditory, auditory-tactile) as the between-subjects factor.

This analysis revealed significant main effects of experiment ($F(1,18) = 14.2$, $p = 0.001$) and distractor frequency ($F(1,18) = 162.6$, $p = 1.88e-10$), but no main effect of distractor type ($F(1,18) = 0.32$, $p = 0.58$). These results indicate that, while there were not obvious differences between CT and AM distractors, the frequency-dependent distraction effects varied according to the tested modality. This is likely due to the fact that lower frequency auditory distractors tended to have larger effects while higher frequency tactile distractors tended to have larger effects. Consistent with this, the experiment x type interaction failed to achieve significance ($F(1,36) = 1.81$, $p = 0.20$), but the remaining interactions were all significant (experiment x frequency interaction: $F(1,18) = 61.3$, $p = 3.22e-07$; type x frequency interaction: $F(1,18) = 7.67$, $p = 0.013$; experiment x type x frequency interaction: $F(1,18) = 8.67$, $p = 0.008$). These interaction patterns reflect strong experiment-specific distractor-frequency effects and more subtle effects of distractor type.

Discussion

We rely on multiple sensory modalities to perceive sequences of repeating sensory events in our environment. In auditory and tactile temporal processing, sensory cues comprising events occurring with low repetition rates are perceived as flutter while those occurring with high repetition rates are perceived as a continuous signal associated with a pitch percept. We found that audition and touch interact reciprocally in the perception of flutter cues. Distractors presented in one modality bias the perception of flutter frequency in the other: A 16-Hz distractor causes a 26-Hz standard stimulus to be experienced as lower in frequency while a 36-Hz distractor causes the same standard stimulus to be experienced as higher in frequency. We also found that flutter information conveyed through click trains and amplitude modulated distractors induced generally similar biasing effects. These results reveal that the bi-directional interactions between audition and touch in temporal frequency perception, which have been extensively characterized at higher frequencies (>100Hz), extend down to the flutter frequency domain.

While auditory and tactile signals mutually influence each other in flutter perception, the interaction patterns associated with each distractor modality are marked by subtle differences. We found that the absolute magnitude of auditory biasing effects on tactile perception tended to be greater than the absolute magnitude of tactile biasing effects on auditory perception. This difference may have been attributable to differences in the sensitivity of auditory and tactile flutter perception, assuming that the auditory and tactile flutter cues are combined in a

statistically optimal manner[28]. We tested this indirectly by estimating auditory and tactile flutter discrimination thresholds to CT and AM signals in a separate experiment conducted with a different sample of participants (Fig. S1). The range of thresholds tended to be similar (CT_T: 1.58 ± 0.24Hz, CT_A: 1.71 ± 0.38Hz, AM_T: 3.75 ± 0.50Hz, AM_A: 2.12 ± 0.32Hz) and the CT thresholds were statistically indistinguishable from the baseline thresholds in experiments 1 and 2 (CT_T: $t(18) = -0.17$, $p = 0.86$; CT_A: $t(18) = 0.87$, $p = 0.40$). Though subtle, the differences in the unimodal thresholds were significantly related to modality (modality main effect: $F(1,9) = 14.38$, $p = 0.004$, $\eta_p^2 = 0.62$) and flutter type (main effect: $F(1,9) = 12.03$, $p = 0.007$, $\eta_p^2 = 0.57$; interaction effect: $F(1,9) = 14.06$, $p = 0.005$, $\eta_p^2 = 0.61$). Based on these thresholds, if the flutter interactions were simply related to sensitivity differences, we would have predicted larger effects with CT distractors compared to AM distractors; however, we did not observe larger effects with CT distractors in either experiment. Furthermore, threshold patterns with audio-tactile flutter signals were also inconsistent with optimal integration. A maximum likelihood estimation model would predict that the thresholds with the combined sensory cues would be lower than those estimated for each cue separately, but we found that thresholds remained unchanged (with tactile distractors) or were elevated (with auditory distractors). Collectively, these interaction patterns imply that auditory and tactile flutter signals were not combined in a statistically optimal manner in our experiments. Our explicit instructions for participants to attend selectively to one modality while ignoring the other may explain this deviation from optimality. Under this context, the goal of the nervous system may not be cue integration, so our paradigm may actually be probing the nervous system's capacity to segregate multisensory cues. Accordingly, auditory distractors may have induced larger biases and elevated thresholds more than tactile distractors because it may simply be more difficult to ignore sounds compared to vibration cues in this context.

Auditory and tactile distractors also appeared to differ in the relative magnitudes of the PSE shifts induced by the low- and high-frequency distractors. With auditory distractors, low frequency signals induced significantly larger biases than high frequency signals. With tactile distractors, high frequency signals tended to induce larger biases than low frequency signals, though this difference was not statistically significant. These asymmetries are beyond the scope of the current study, but it is notable that lower frequency sounds also exert greater influences on vibrations compared to higher frequency sounds for signals exceeding 100Hz[9]. Based on interaction patterns in high frequency processing, we previously speculated that this asymmetry could reflect the tuning properties of cortical neurons which may be patterned on the statistics of

our sensory experiences[9], and our current results extend this logic to processing in the flutter domain. Indeed, the final estimate computed from the integration of any pair of auditory and tactile signals in a Bayesian framework[29] would also depend on the prior likelihoods reflecting the history of co-occurring audio-tactile signals; if tactile signals tend to be slightly lower in frequency than co-occurring auditory signals in our lifetime of experiences, such a prior could explain the asymmetric PSE patterns in both of our experiments. In the future, it will be important to measure the actual statistics of our audio-tactile experiences to test Bayesian accounts of audio-tactile integration explicitly.

We investigated whether audio-tactile interactions in flutter processing differ when click trains and amplitude modulated signals are tested. One possibility was that flutter interactions would only be observed when the auditory and tactile stimulus type matched. Because CT and AM signals may be represented by distinct neural populations[25–27], interactions mediated by these populations would presumably be sensitive to stimulus type. Furthermore, because CT and AM signals are so perceptually distinct, the interactions between CT and AM signals may have been weaker if flutter interactions depended on the inference of a common cause under a causal inference framework[30]. The other possibility was that auditory and tactile flutter interactions occur irrespective of stimulus type. This result would imply that auditory and tactile flutter processing converges on neural populations that support flutter representations which are invariant to stimulus type. We found little evidence that flutter information is combined over the senses in manners that strongly depend on stimulus type. This result could also imply that audio-tactile interactions in flutter processing occur at decisional levels where the flutter information has already been extracted from each stimulus and modality.

What neural populations mediate interactions between auditory and tactile flutter? There have been extensive studies on the neural coding of tactile flutter[2,31,32] and auditory flutter[5,33,34] that have mapped perceptual decision making processes to the sensory and frontal cortices. Recent studies have identified neural populations in traditionally-defined sensory cortices that respond to flutter signals experienced in both modalities[22]; however, the weak relationship between perception and the crossmodal activity in these areas implies that multimodal encoding and perceptual judgments are supported by neurons residing in regions outside of the sensory cortices[22]. These population may instead be found in frontal regions like pre-supplementary motor area[23] and medial premotor cortex[35] where individual neurons represent auditory and tactile flutter analogously. While neurons in frontal regions have been shown to support unimodal comparisons between pairs of tactile signals or auditory signals and crossmodal

comparisons between tactile and auditory signals, the role of these neurons in representing combinations of co-occurring auditory and tactile signals remains to be tested. It will also be critical to determine whether the neural populations which represent auditory and tactile flutter also encode visual flicker[36], particularly because auditory flutter and visual flicker interact strongly in rate perception[24,37–41].

Audition and touch are known to interact reciprocally in the processing of signals comprising frequencies greater than 100Hz[7–11]. The nervous system may exploit multisensory information in this frequency domain to support texture perception[42–44] and sensorimotor processing of fundamental frequencies in speech[45]. Here, we extended the frequency range over which audition and touch interact to the flutter domain. These findings provide yet another example of how the nervous system combines analogous information across sensory modalities. Our psychophysical results can motivate future neurophysiological studies aimed at identifying the neural substrates which underlie multisensory flutter interactions. Moreover, given the importance of slow temporal variations in the speech processing[46] and other behaviors, our findings highlight new ways in which multisensory processes may be leveraged in neurorehabilitation or sensory substitution approaches.

Methods

Participants
A total of 38 subjects were recruited for the study. Thirteen subjects (8 females; 20.1 ± 1.32 years; 1 left handed) were recruited for experiment 1. Sixteen subjects (9 females; 22.9 ± 6.11 years; 1 left handed) were recruited for experiment 2. Thirteen subjects (10 females, mean age ± SD 22.4 ± 7.69 years; 1 left handed) were recruited for the experiment characterizing unimodal flutter discrimination (see Supplementary information). One subject participated in experiments 1 and 2. Two subjects participated to both the unimodal experiment and one of the main experiments. No participant reported a neurological or psychiatric history. All participants reported normal tactile and auditory sensibilities. All testing procedures were conducted in compliance with the policies and procedures of the Baylor College of Medicine Institutional Review Board. All participants gave their written informed consent and were paid for their participation.

Tactile and auditory stimulation

Tactile and auditory stimuli tested in all three experiments were digitally generated (sample rate: 44.1kHz) in Matlab (2011b, MathWorks) and presented with Psychtoolbox-3 (Kleiner et al., 2007) running on a MacBook Pro (model A1278; OS X 10.9.5, 2.5 GHz Core i5, 4 GB of RAM). Tactile stimuli were analog signals passed through one channel of the auxiliary port to a power amplifier (Krohn-Hite Wideband Power Amplifier, model 7500) and delivered to the subject's right index finger through an electromechanical tactor (type C-2, Engineering Acoustics, Inc). The tactor was fastened to the distal phalange on the right index finger using self-adherent cohesive wrap bandages. Subjects maintained their hand in a supinated posture during the test blocks. Auditory stimuli consisted of analog signals from the second channel of the auxiliary port. These signals were amplified (PTA2, Pyle) and delivered binaurally via noise-cancelling in-ear headphones (ATH-ANC23, Audio-Technica U.S., Inc). In all experiments, subjects also wore noise-attenuating earmuffs (Peltor H10A Optime 105 Earmuff, 3M) over the in-ear headphones, to attenuate any noise produced by the tactor.

Two types of flutter stimulation were tested during the experiments. Amplitude modulated (AM) signals (duration: 1 sec) were generated with the function:

$$p(t) = [1 + m * \sin(2\pi f_{mod} t)] * \sin(2\pi f_c t)$$

where t is time, m is the modulation index (set to 1 for a modulation depth of 100%), f_c is the carrier frequency (200Hz), and f_{mod} is the frequency of the modulation envelope which ranged from 16-36Hz. Click train (CT) signals consisted of 1-sec trains of monopolar, rectangular pulses (pulse duration: 3 msec). The number of pulses in each click train ranged from 16-36.

General procedures
Before performing the main experimental task, subjects were trained to perform flutter discrimination separately in the auditory and the tactile modality. Subjects who could not perform the discrimination task reliably were excluded from the main study. A total of 11 subjects were excluded across the full study (experiment 1: 3, experiment 2: 6, unimodal experiment: 3). Experiments 1 and 2 were split into two separate sessions of approximately 1.5 hrs each, conducted on different days (mean inter-session interval ± SD, experiment 1: 6.5 ± 4.7; experiment 2: 4 ± 3.3 days).

Flutter discrimination task
Participants discriminated between two flutter stimuli (inter-stimulus interval: 0.8 sec) and reported which stimulus was perceived to be higher in frequency in a 2-interval, 2-alternative

forced choice paradigm. On each trial, one interval contained the standard stimulus whose frequency (f_s) was always a 26 Hz flutter. The other interval contained a comparison stimulus whose frequency (f_c) was 16, 20, 24, 28, 32, or 36Hz. The interval containing the standard stimulus was randomized across trials. To ensure that participants could not perform the frequency discrimination task using stimulus intensity cues, each stimulus was delivered at the same nominal amplitude but with a random jitter (±10%). Subjects maintained their gaze on a central fixation cross on a computer screen and reported their decision by button press using their left hand.

In each experiment, participants were instructed to attend to one modality (targets) while ignoring stimulation in the other (distractors). In experiment 1, the targets were tactile flutter cues. In experiment 2, the targets were auditory flutter cues. During each experiment, distractors co-occurred with the targets on 80% of the trials. Distractors were either a pair of CT or AM stimuli (equal probability). The frequency of the distractor co-occurring with the standard stimulus was either 16 (low frequency distractor) or 36Hz (high frequency distractor). The frequency of the distractor always matched the frequency of the target in the comparison interval. No distractors were presented in the remaining 20% of the trials and performance on these trials established baselines against which performance achieved with distractors could be compared.

Experiment 1: Tactile flutter discrimination with auditory distractors
We tested whether auditory CT and AM distractors influenced the perception of tactile CT stimuli. For each subject, each comparison stimulus in each distractor condition (low, high, baseline) was repeated 40 times for a total of 1200 trials over two sessions. Each session was divided into 10 blocks. Subjects were provided rest intervals between each block.

Experiment 2: Auditory flutter discrimination with tactile distractors
We tested whether tactile CT and AM distractors influenced the perception of auditory CT stimuli. For each subject, each comparison stimulus in each distractor condition (low, high, baseline) was repeated 40 times for a total of 1200 trials over two sessions. Each session was divided into 10 blocks. Subjects were provided rest intervals between each block.

Data analysis

All statistical analyses were performed in Matlab. Normality was tested using Kolmogorov-Smirnov tests.

Each participant's choice probability data were fitted with a Gaussian cumulative distribution function (cdf):

$$p(f_c > f_s) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{f_c - \mu}{\sigma\sqrt{2}}\right)\right]$$

where $p(f_c > f_s)$ is the probability that a given f_c was judged to be higher in frequency than f_s, $\mathrm{erf}(x)$ is the error function of x, and μ and σ are free parameters that represent the participant's point of subjective equality (PSE) and just-noticeable difference (JND), respectively. The PSE is a measure of the perceptual bias and corresponds to the f_c perceived as equal in frequency to the f_s. The JND is a measure of the perceptual threshold corresponding to the frequency change (with respect to the standard frequency) that the participant can detect 84% of the time.

Group-level analysis

We used the same statistical approach to analyze the data from experiments 1 and 2. To test whether PSE and JND differed in any condition, we first conducted a one-way repeated-measures ANOVA, with distractor condition (5 levels: baseline and 4 distractor conditions) as within-subjects factor. If this test was significant ($p < 0.05$), we then conducted a two-way rmANOVA with distractor type (2 levels: CT, AM) and distractor frequency (2 levels: 16Hz, 36Hz) as within-subjects factors. To compare distractor effects between experiments 1 and 2, we performed a mixed-design ANOVA with distractor type (2 levels: CT, AM), distractor frequency (2 levels: 16Hz, 36Hz) as within-subjects factors and experiment (which was a proxy for the test and distractor modality pairings in each experiment; 2 levels: tactile-auditory, auditory-tactile) as the between-subjects factor.

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Author contributions

S.C. and J.M.Y. designed the study and wrote the manuscript. S.C. and K.W.C. performed the experiments and analyzed the data. All authors contributed to the final revisions of the manuscript.

Competing interests

The authors declare no competing interests.

Data availability

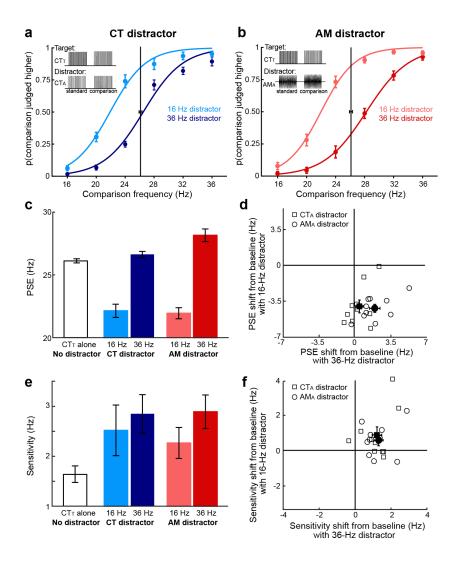Behavioral data (.mat files) are available at https://github.com/YauLab/AT_Flutter

Figure 1. Tactile flutter discrimination with and without auditory distractors. n = 10 **(a, b)** Group averaged choice probability data and psychometric functions in the presence of auditory click train (a) and amplitude modulated (b) distractors. Lighter traces indicate performance with 16-Hz distractors. Darker traces indicate performance with 36-Hz distractors. Black vertical lines represent mean PSE in trials without distractors. **(c)** Average PSE estimates under baseline and distractor conditions. **(d)** Baseline-corrected PSE estimates with low- and high-frequency distractors. Open markers indicate data for individual subjects. Filled markers indicate group average. **(e)** Average JND (sensitivity) estimates under baseline and distractor conditions. **(f)** Baseline-corrected JND estimates with low- and high-frequency distractors. Open markers indicate data for individual subjects. Filled markers indicate group average. Error bars indicate s.e.m.
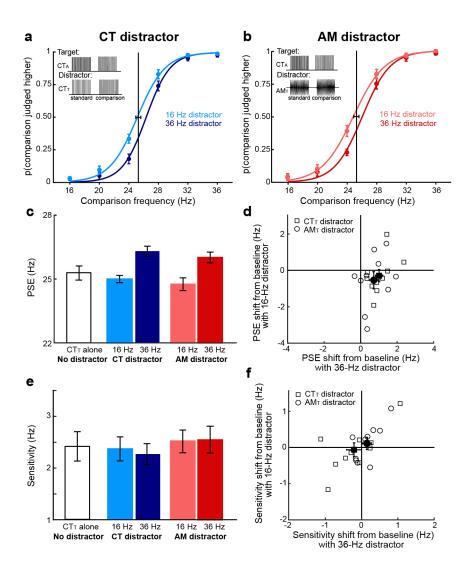
Figure 2. Auditory flutter discrimination with and without tactile distractors. n = 10 **(a, b)** Group averaged choice probability data and psychometric functions in the presence of tactile click train (a) and amplitude modulated (b) distractors. Lighter traces indicate performance with 16-Hz distractors. Darker traces indicate performance with 36-Hz distractors. Black vertical lines represent mean PSE in trials without distractors. **(c)** Average PSE estimates under baseline and distractor conditions. **(d)** Baseline-corrected PSE estimates with low- and high-frequency distractors. Open markers indicate data for individual subjects. Filled markers indicate group average. **(e)** Average JND (sensitivity) estimates under baseline and distractor conditions. **(f)** Baseline-corrected JND estimates with low- and high-frequency distractors. Open markers indicate data for individual subjects. Filled markers indicate group average. Error bars indicate s.e.m.