Determining individual decibel thresholds for target values in the auditory oddball paradigm

We determined how much to lower the decibel level for target tones on an individual basis, using a transformed up-down staircase procedure from the PSYCHOACOUSTICS toolbox in Matlab (Soranzo & Grassi, 2014). For this, participants listened to sets of three tones and determined which was the loudest. The loudest tone started at 10 decibels higher than the other two tones in the sequence. If the participant correctly identified the loudest tone twice, the algorithm then began working down a *staircase* of decreasing decibel differences, going down one *step* each time the participant correctly identified two tones at that decibel level, and increasing one *step* each time the participant incorrectly identified the loudest tone at that decibel level. Each block continued until the participant hit 12 *reversals*, or changes from going down the staircase to going up the staircase. There were three total blocks. Decibel levels decreased by a factor of two (e.g. 10 decibels to 5 decibels) for the first four reversals, then decreased by a factor of 1.4 (e.g. 10 decibels to 7.14 decibels) for the final eight reversals. The final threshold was then calculated by averaging the decibel levels at the last eight reversals, then averaging these over the all three participation blocks. We then applied this threshold to our target tones.

Reliable differences in individual pupil responses are present in all four testing conditions

To determine whether participants reliably differed in their tendency to entrain their continuous pupillary fluctuations to the rhythmic interval of the tones in the oddball task, we established that participants' pupils reliably responded to our standard and target conditions, but we also investigated the reliability of participants' pupil responses to novel and omission conditions. To do this, we tested the similarity of their averaged pupil responses in each of these two trial-types of the oddball experiment across testing sessions. Pearson correlations compared participants' pupil response curves in each session to their own responses from different sessions. We then compared the resulting R values from those correlations to the R values obtained by correlating pupil responses between participants. Because our data was not normally distributed (within-participant correlations were skewed toward higher R values) and because we had more between-participants observations than within-participants observations, we used the non-parametric Mann-Whitney U test to compare pupil response similarity within and between participants.

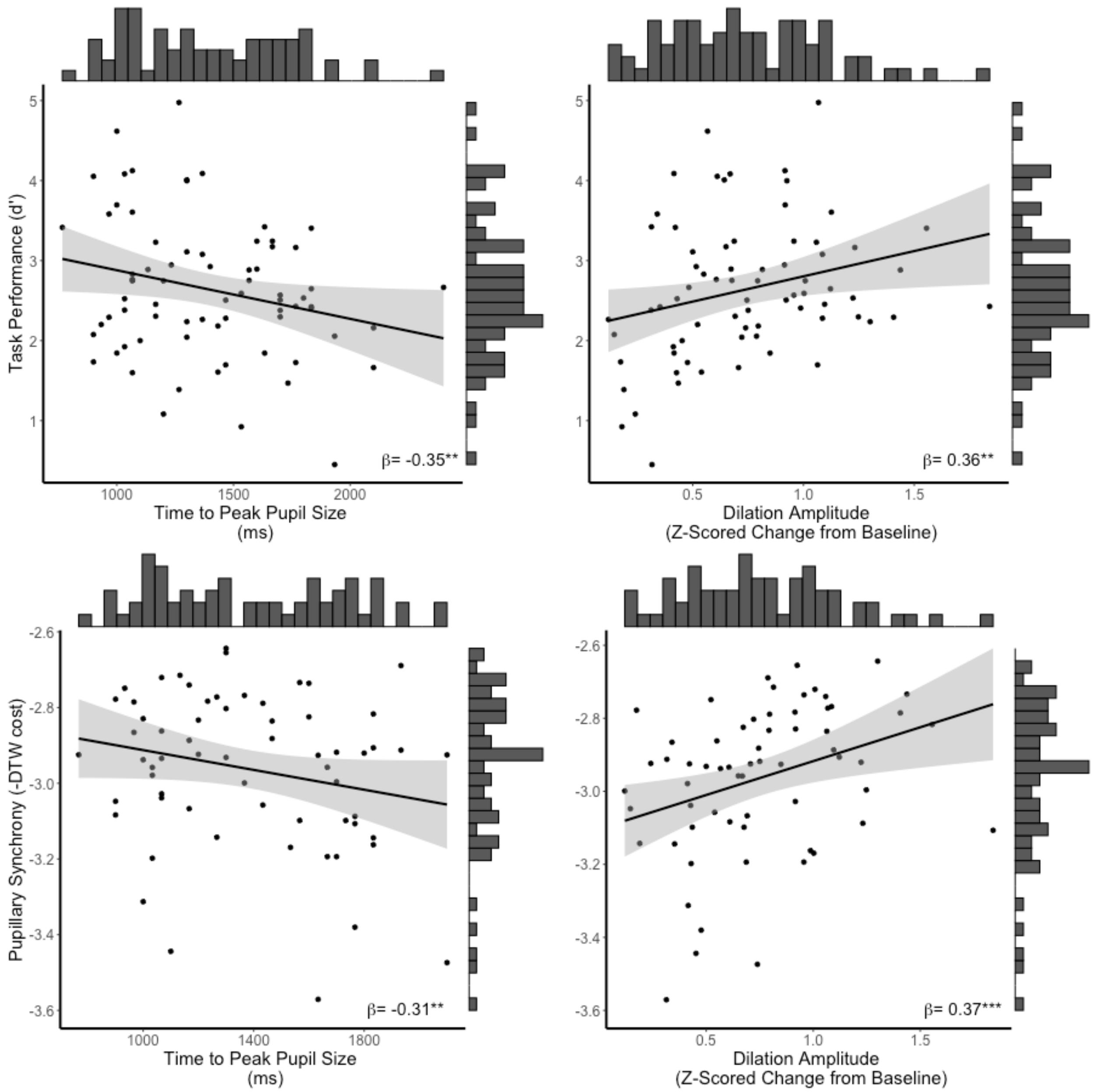
Participants' pupil response curves to novel tones ($U=42812$, $p < 0.001$, cohen's $d = 0.82$) and omission tones ($U=49963$, $p < 0.001$, cohen's $d = 0.69$) were more similar to themselves across sessions than compared to other participants, further supporting the idea that an individual's pupillary fluctuations reflect a stable individual difference throughout the oddball task.

Individual pupillary responses predict oddball detection and pupillary synchrony during storytelling

Because we found that pupil responses to all four tone conditions, in addition to pupillary entrainment, were individually specific and reliable across testing sessions, we wondered whether features of these individual pupil responses across conditions were also predictive of task performance as well as pupillary synchrony with a speaker. To test whether pupillary responses predicted performance (as measured by *d* prime) and speaker-listener synchrony, we ran two linear regressions predicting 1) participants' *d* prime scores and 2) participants' synchrony scores from two features of their pupil response curve, per condition—the maximum amplitude of their pupil response and the time their pupil took to reach this maximum amplitude (tmax). These two features were selected based on Hoeks & Levelt's (1993) paper modeling attention-related pupil responses as impulse response functions triggered by attentional pulses. According to Hoeks and Levelt (1993), amplitude and tmax are two of three parameters that characterize the shape of pupil responses. The third free-varying parameter in their model accounted for the additive nature of attention pulses. This third feature did not pertain to the current study due to the spacing of trials, and is not included here.

A model examining the relationship between oddball task performance and individual pupillary responses during target conditions was significant ($f(3,68) = 4.97$, $p < 0.005$, adjusted $R^2 = 0.14$). target pupil response amplitude positively predicted task performance (target detection sensitivity, measured by *d* prime; $\beta=0.36$, FDR corrected $p<0.01$), such that the greater the dilation, the better the performance on the oddball task. target pupil response tmax inversely predicted task performance ($\beta=-0.35$, FDR corrected $p<0.01$), such that the faster participants' pupils dilated, the better they performed. These relationships are illustrated in supplementary figures 1a and 1b.

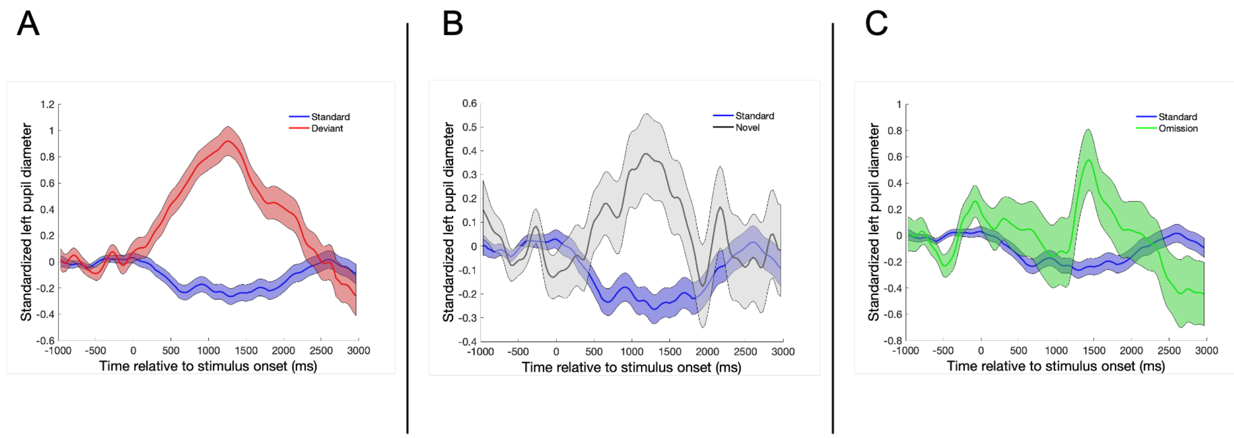
A linear mixed effects model examining the relationship between speaker-listener pupillary synchrony and individual pupillary responses during target conditions was also significant. target pupil response amplitude positively predicted speaker-listener pupillary synchrony ($t(59.9) = 3.8$, $\beta = 0.37$, $p < 0.001$), such that the greater the target dilation during the oddball task, the more synchrony with a speaker telling a story. target pupil response tmax inversely predicted speaker-listener pupillary synchrony ($t(60.1) = -3.2$, $\beta = -0.31$, $p < 0.005$), such that the faster participants' pupils dilated during the oddball task, the more synchrony with a speaker telling a story. These relationships are illustrated in supplementary figures 1c and 1d.



Supplementary Figure 1. Data and estimated slopes for the relationship between 1) task performance and **A)** time to peak pupil size (tmax) and **B)** amplitude, and 2) pupillary synchrony between speakers and listeners with **C)** tmax of listeners' attention related pupil responses during the oddball task and **D)** amplitude of listeners' attention related pupil responses during the oddball task. Tmax was negatively related to both task performance and pupillary synchrony such that the quicker participants reached peak pupil dilation, the better they performed on the oddball task and the more synchronous they were with a speaker telling stories. Amplitude was positively related to task performance and pupillary synchrony such that the larger participants' attention-related pupil responses were, the better they performed on the oddball task and the more synchronous they were with a speaker telling stories.

We then investigated whether individual pupil responses to the other three conditions were also predictive of task performance and speaker-listener synchrony. Because we found that pupillary entrainment was predictive of task performance, we hypothesized that participants' entrained pupillary fluctuations with the rhythm of the oddball sequence could be explained by individual differences in participants' *predictions* for upcoming target events, since previous studies have suggested entrainment as a possible outcome of implicit learning and anticipatory attending (Jones, 2010; Jones et al., 2006; Large & Jones, n.d.). Thus, we hypothesized that for novel trials, which were placed randomly throughout the sequence of tones and thus unexpected, there would be no relationship between pupil responses and task performance. Consistent with this hypothesis, pupil responses to novel trials were not predictive of task performance ($f(3,68) = 1.78$, $p = 0.16$, adjusted $R^2 = 0.03$). However, when we examined *omission* trials, which were similarly unexpected to novel trials, but placed in expected locations in the sequence, we found that the same effects persisted as were found for target trials, further supporting the idea that these pupillary responses were indexing predictions about upcoming tones in the sequence. Omission trials significantly predicted task performance ($f(3,68) = 3.72$, $p < 0.02$, adjusted $R^2 = 0.1$), with amplitude positively relating to task performance ($\beta = 0.35$, FDR corrected $p < 0.01$) and tmax negatively relating to task performance ($\beta = -0.25$, FDR corrected $p = 0.05$).

We did not find that pupil responses to standard trials predicted task performance ($f(3,68) = 1.26$, $p = 0.3$, adjusted $R^2 = 0.01$). This was initially surprising, since we do find that entrained pupillary fluctuations at the interval of the standard tone does predict task performance. However, we noticed that participants' pupil responses to standard trials were on average much smaller than their responses during all of the other conditions (see supplementary figure 2). Because standard tones occurred predictably and frequently throughout the task, and because participants were not directly instructed to attend to standard tones, this result could simply be due to the muted response to these tones across participants.



Supplementary Figure 2. Illustration of attention-related pupil responses from a single participant for **A)** target trials, **B)** novel trials, and **C)** omission trials. Pupil responses to standard trials are plotted for comparison in all three figures.

We found no relationship between speaker-listener pupillary synchrony and attention related pupil responses from any of the other three oddball conditions (novel, omission, standard). One hypothesized explanation for this is that pupillary synchrony between speakers and listeners could primarily be driven by highly anticipated story moments, during which both speakers and listeners are fully locked-in to the content of the narrative. These are moments that also correspond to the anticipated target tones in the oddball task, but no other conditions.

Testing the relationship between individual differences in pupillary correlates of attention and reaction time in the auditory oddball paradigm

We found that individuals' predictive attention-related pupil responses and their ability to entrain to the oddball task structure both predicted their target detection performance during the oddball task. We wondered whether participants' reaction times when identifying target tones would show a similar relationship. We ran linear regressions predicting participants' reaction time from their response amplitude and tmax and from their task entrainment power. This model was significant for pupil responses to the target condition ($f(3,67) = 5.18$, $p = 0.002$, adjusted $R^2 = 0.15$). This model fit was driven by tmax, which positively predicted reaction time ($\beta=0.39$, FDR corrected $p=0.01$), such that the quicker participants reacted to the target, the quicker their pupils dilated. Amplitude did not significantly relate to reaction time ($\beta=-0.02$, FDR corrected $p=0.9$). Omission trials also significantly predicted reaction time ($f(3,67) = 4.08$, $p = 0.01$, adjusted $R^2 = 0.12$). This model fit was primarily driven by the interaction between amplitude and tmax ($\beta=0.32$,FDR corrected $p=0.03$), such that the positive relationship between reaction time and tmax was enhanced for participants who had larger dilation amplitude. There were no significant effects associated with novel trials ($f(3,67) = 0.56$, $p = 0.65$, adjusted $R^2 = -0.019$), standard trials ($f(3,67) = 1.32$, $p = 0.27$, adjusted $R^2 = 0.01$), or entrainment power ($f(1,69) = 2.95$, $p = 0.09$, adjusted $R^2 = 0.03$) predicting reaction time to target events. These results suggest a similar but attenuated relationship to the relationship found for task performance. This could be due to participants with quick reaction times but low task performance, who may be quick to respond *incorrectly*.

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