

A supramodal and conceptual representation of subsecond time revealed with perceptual learning of temporal interval discrimination

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Subsecond time perception has been frequently attributed to modality specific timing mechanisms that would predict no cross modal transfer of temporal perceptual learning. In fact, perceptual learning of temporal interval discrimination (TID) reportedly shows either no cross modal transfer,

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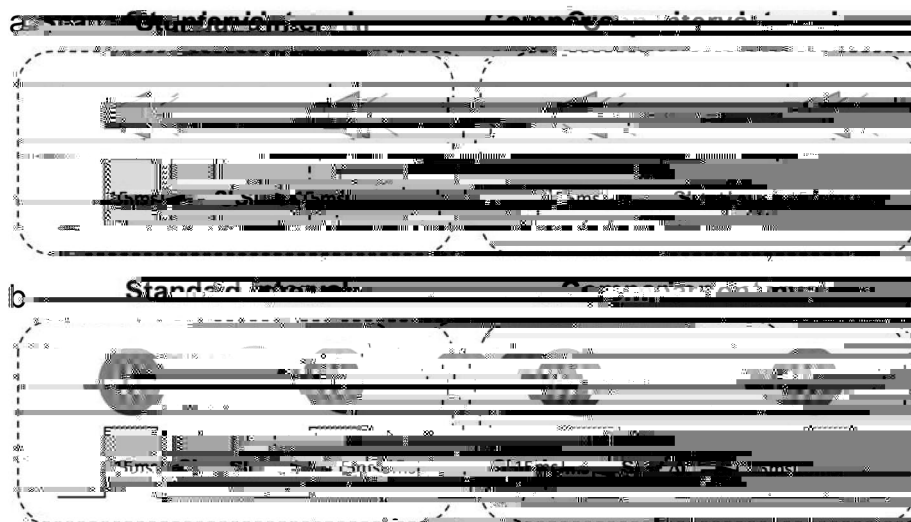


Fig. 1 Illustrations of auditory and visual TID trials. (a) An auditory TID trial. The standard stimuli were two 15-ms tone pips separated by a 100 ms interval, and the comparison stimuli were the same two tone pips separated by a 100+ ms interval. In a given trial, the standard and comparison stimuli were presented in random order with a 900 ms time gap. (b) A visual TID trial. The same as the auditory TID trial except that the tone-pips were replaced with Gabor patches.

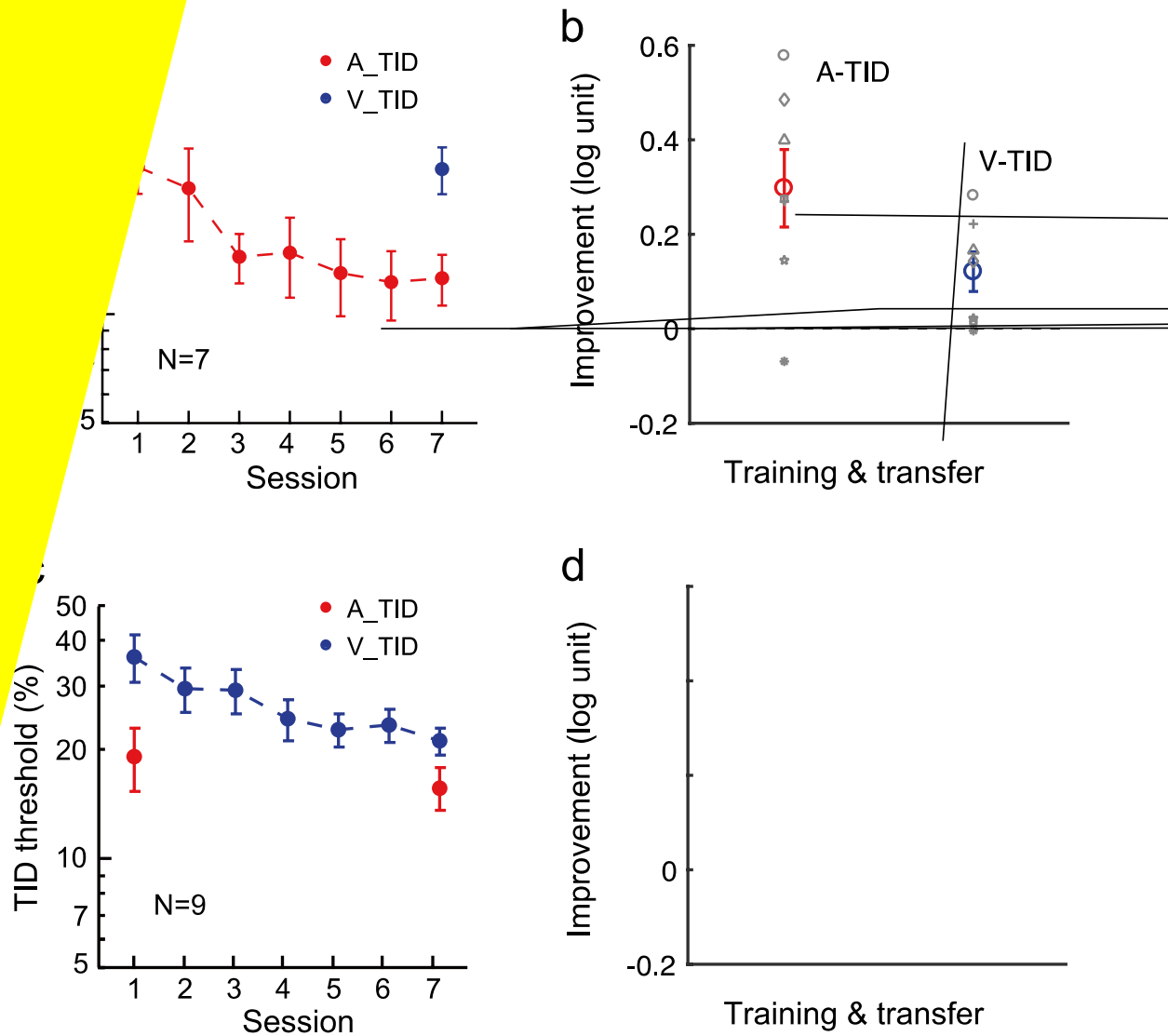
The goal of this study is to demonstrate mutual and complete transfer of visual and auditory TID learning, so as to prove a supramodal subsecond time representation. Our previous perceptual learning studies have shown that various forms of specificities are not necessarily innate properties of perceptual learning as commonly believed, and can be eliminated with a double-training procedure^{21–23}. In contrast to conventional training in which only the task of interest is practiced, double training consists of two training tasks. The primary training task in the current context would be TID in one sense (e.g., audition), and the secondary training task would be a functionally orthogonal one, such as contrast discrimination, in a new sense (e.g., vision). Here in the contrast discrimination task, the two Gabor gratings in a two-alternative forced-choice trial would mostly have near-threshold contrast differences and be presented at the same temporal interval as in the primary task, so that the participants would receive exposure to the temporal interval passively, but their attention is directed to near-threshold contrast discrimination to prevent potential temporal learning with the secondary task. The secondary task thus may activate sensory neurons representing the temporal interval in the new sense, so that the potential supramodal TID learning could functionally connect to temporal inputs from the new sense to improve TID performance. Double training has successfully enabled learning transfer of various visual discrimination tasks to untrained retinal location, orientation, motion direction, etc.^{21,22,24–26}. It also succeeded in transferring auditory²⁷ and visuomotor learning^{28,29}.

Most relevant to the current study is our recent report that perceptual learning of tactile orientation discrimination can transfer completely to visual orientation discrimination after double training, even if no transfer was evident with conventional single training³⁰. These results are interpreted as evidence for a supramodal representation of stimulus orientation. Moreover, since the tactile orientation threshold is about three times as high as the visual orientation threshold, learning transfer is possible only if the supramodal representation is abstract and conceptual, independent of the original modality precision of sensory inputs^{30,31}. Following the same reasoning, here we hypothesized that if perceptual learning of auditory and visual TID, which also differ in precision, could transfer mutually and completely with double training, we would also have evidence for a supramodal representation of subsecond time at a conceptual level.

Results

Baselines: asymmetric learning transfer between auditory and visual TID with conventional single training. We first measured the cross-modal transfer of TID learning between audition and vision with conventional single training, which established baselines for later double training experiments. One group of participants ($N=7$) practiced auditory TID (auditory single-training group), and a second group ($N=9$) practiced visual TID (visual single-training group), both with the 100-ms standard interval.

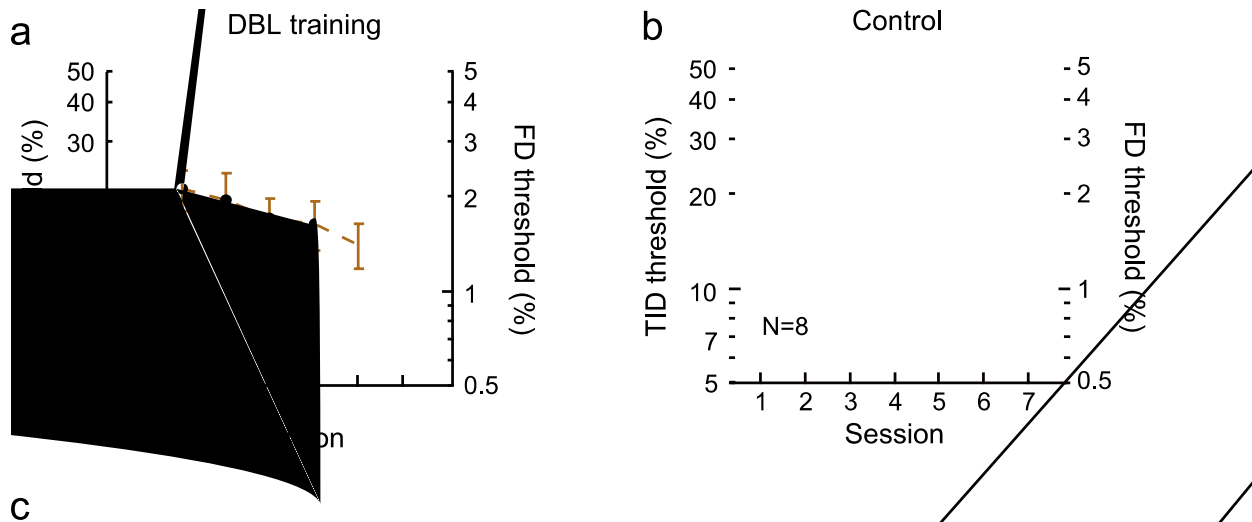
For the auditory single-training group, training reduced auditory TID threshold by 0.30 ± 0.08 log units ($t_6 = 3.63, p = 0.011, \text{Cohen's } d = 1.37$). The same training also improved visual TID at the same 100-ms interval, reducing visual TID threshold by 0.12 ± 0.04 log units ($t_6 = 3.87, p = 0.029, \text{Cohen's } d = 1.08$) (Fig. 2a, b). However, for the visual single-training group, although training improved visual TID by 0.20 ± 0.05 log units ($t_8 = 3.81, p = 0.005, \text{Cohen's } d = 1.27$), the learning did not transfer to auditory TID at the same interval (by 0.05 ± 0.05 log units; $t_8 = 1.04, p = 0.33, \text{Cohen's } d = 0.35$) (Fig. 2c, d). These results thus confirmed previous reports of asymmetric audition-to-vision transfer of TID learning with conventional single training^{8,9}. Here the visual TID improvement through auditory TID training (V_TID in Fig. 2b) was about 60% of that through direct visual TID training



(V_TID in Fig. 2d), suggesting that auditory TID training might have not maximized the visual TID performance in these observers. In other words, the audition-to-vision learning transfer was partial.

Double training: complete vision to audition transfer of TID learning. Next, we examined whether visual TID learning could transfer to auditory TID with double training. Nine participants practiced visual TID at a 100-ms interval. They also received exposure to the auditory 100-ms interval by practicing an orthogonal tone frequency discrimination task at the same interval. This double training improved visual TID by 0.21 ± 0.03 log units ($t_8 = 6.54$, $p < 0.001$, Cohen's $d = 2.18$) and tone frequency discrimination by 0.17 ± 0.05 log units ($t_8 = 3.44$, $p = 0.009$, Cohen's $d = 1.15$) (Fig. 3a, c). Importantly, auditory TID at the same interval also showed an improvement of 0.24 ± 0.04 log units ($t_8 = 5.92$, $p < 0.001$, Cohen's $d = 1.97$) (Fig. 3c), which was not significantly different from the 0.29 log-unit improvement with direct auditory TID training in the auditory single-training group (Fig. 2b) ($t_{14} = 0.63$, $p = 0.54$, Cohen's $d = 0.31$). Therefore, auditory TID appeared to have maximized after visual TID training and tone frequency discrimination training were coupled in double training, even if it was unaffected by visual TID training alone (Fig. 2c, d).

To exclude the possibility that the auditory TID improvement was simply a result of tone frequency discrimination training, we had a control group ($N = 8$) only practice tone frequency discrimination at a 100-ms interval. The practice improved tone frequency discrimination by 0.17 ± 0.05 log units ($t_7 = 3.27$, $p = 0.014$, Cohen's $d = 1.16$), but it failed to improve auditory TID at the same interval (by -0.03 ± 0.07 log units; $t_7 = -0.43$, $p = 0.68$,



Cohen's $d = -0.15$, Fig. 3b, c). Taken together, the double training results and control data suggested that double training enabled full learning transfer from visual TID to auditory TID, in spite of the insignificant transfer in the single-training condition (Fig. 2c, d).

To reduce Type-I errors in our data analysis, a between-subject ANOVA compared auditory TID improvements among the three training conditions, i.e. single visual TID training, current double training, and tone frequency discrimination training. The ANOVA outputs suggested a significant main effect of training condition ($F_{2, 24} = 7.70, p = 0.003, \eta^2 = 0.39$). Further contrast analysis showed that the auditory TID improvement after double training was significantly higher than the improvement after single visual TID training ($t_{24} = 2.60, p = 0.016$) and the improvement after tone frequency discrimination training ($t_{26} = 2.69, p = 0.012$).

Double training: complete audition to vision transfer of TID learning. Earlier we suggested that visual TID improvement after auditory TID training was approximately 60% of that after direct visual TID training (Fig. 2b, d). Here we examined whether double training could lead to complete audition-to-vision TID learning transfer. Eight new participants practiced auditory TID and visual contrast discrimination, both at a 100-ms interval, in alternating blocks of trials in the same training sessions. Training improved auditory TID by

0.29 ± 0.04 log units ($t_7 = 6.55$, $p < 0.001$, Cohen's $d = 2.32$) and visual contrast discrimination by 0.37 ± 0.20 in d' ($t_7 = 2.06$, $p = 0.058$, Cohen's $d = 0.73$), as well as visual TID at the same interval by 0.26 ± 0.03 log units ($t_7 = 8.21$, $p < 0.001$, Cohen's $d = 2.90$) (Fig. 4a, c). The visual TID improvement did not differ significantly from the 0.20 log-unit improvement through direct visual TID training (Fig. 2c) ($t_{15} = 1.03$, $p = 0.31$, Cohen's $d = 0.50$), suggesting that the visual TID performance had maximized after double training.

Again, a control group of participants ($N = 8$) practiced visual contrast discrimination only, which improved contrast threshold by 0.84 ± 0.15 in d' ($t_7 = 4.74$, $p < 0.001$, Cohen's $d = 1.68$). But this practice had no significant impact on visual TID at the same 100-ms interval (by 0.04 ± 0.03 log units; $t_7 = 1.13$, $p = 0.30$, Cohen's $d = 0.30$, Fig. 4b, c), excluding the possibility that contrast discrimination training per se was responsible for above visual TID learning after double training. Here the visual pretraining threshold (V_TID) appeared to be lower than that with the double training group, which was mainly due to one participant who showed very low pre-training threshold at 11.8%. The pre-training V-TID thresholds were not significantly different from each other ($p = 0.146$,

rate of 160 Hz. The luminance of the monitor was linearized by an 8-bit look-up table, with a mean luminance of 43.5 cd/m². A chin-and-head rest stabilized the head of the observer.

Stimuli and procedures. The auditory stimuli were two 15-ms tone pips separated by a 100 ms standard temporal interval (Fig. 1a). Each tone contained a 5-ms cosine ramp at each end, and was fixed at 1 kHz and 86 dB SPL. The visual stimuli were two 15-ms Gabor gratings, also separated by a 100 ms interval (Fig. 1b). Each Gabor had a fixed orientation (vertical), spatial frequency (1 cycle/deg), and contrast (100%). The length of the interval was the difference between the onset of the first stimulus and the onset of the second stimulus. We used 100 ms as the standard temporal interval because previous studies had shown clear evidence for significant TID learning and asymmetric audition-to-vision learning transfer at this interval⁸.

The TID threshold was measured with a method of constant stimuli. In each forced-choice trial, a visual fixation was first centered on the computer screen for 300 ms, then two pairs of stimuli, one with a standard interval (100 ms) and the other with a comparison interval (100 ms + Δt), were subsequently presented in random order with a 900-ms time gap. The participants pressed the left or right arrow to indicate whether the first or the second pair of stimuli had a longer interval. A happy or sad cartoon face was shown on the screen after each response to indicate a correct or wrong response. A blank screen was presented before the next trial for a random duration (500–1000 ms). The Δt was set at 6 levels for each condition (auditory TID: $\pm 20.1, \pm 13.4, \pm 6.7$ ms; visual TID: $\pm 33.5, \pm 20.1, \pm 6.7$ ms), and the intervals between stimulus levels were increased if necessary to ensure a sufficient range of correct rates. Each level was repeated 10 times in a block of 60 trials, for a total of 5 blocks.

The psychometric function was fitted with $P = \frac{1}{1 + e^{(-k) * (\Delta t - \Delta t_0)}}$, where P was the rate of reporting the comparison interval being longer at each Δt , k was the slope, and Δt_0 was the point of subjective equivalence. The TID threshold was equal to half the interquartile range of the function: $\text{threshold} = (\Delta t_{75} - \Delta t_{25})/2$.

The stimuli for tone frequency discrimination were the same as those for auditory temporal interval discrimination, except that the frequencies of two pairs of pips were changed while the temporal intervals were fixed at 100 ms. Two pairs of tone pips, one pair at a standard frequency of 1 kHz and the other at a higher comparison frequency (1 kHz + Δf), were presented subsequently in a random order in each trial. The participants pressed the left or right arrow to indicate whether the first or second pair of tone pips had a higher frequency. A happy or sad cartoon face was provided as feedback.

The tone frequency discrimination threshold was measured with a temporal 2AFC staircase procedure. The starting frequency difference (Δf) between the standard and comparison stimuli was 50%, which decreased by a factor of 2 after every correct response until the first incorrect response. Then the Δf was varied by a factor of 1.414 following a 3-down-1-up staircase rule for a 79% correct rate. Each staircase ended after 60 trials. The threshold was calculated as the mean of the last 40 trials.

The stimuli used for visual contrast discrimination were the same as those for visual temporal interval discrimination, except that the Gabor contrast was varied while the interval was fixed (100 ms). Only one pair of Gabors was presented in each trial. In 80% of the trials, the two Gabors had identical contrast, which randomized from 0.15 to 1. In the remaining 20% trials, the contrasts of two Gabors differed by 50%. The participants judged whether two Gabors had identical contrast. A happy or sad cartoon face was provided as feedback. The d' value was calculated to measure the contrast discrimination performance.

Each experiment consisted of a pre-training session, five training sessions, and a post-training session on separate days. The experiment was completed within 7–13 days, with inter-session gaps of no more than 2 days. Each single-training session consisted of 16 blocks of trials and lasted for approximately 1.5 h. Each double-training session consisted of 10 blocks of trials for the primary task and 10 blocks of trials for the secondary task in an alternating order, and lasted for approximately 2 h.

Sample size. The sample size was decided on the basis of a previous TID learning study that used similar stimuli (100 ms–1 kHz condition in Fig. 4, ref.¹⁸). In our study, learning and transfer involved comparisons between pre- to post-training thresholds in all experiments. To achieve 80% power at $p = 0.05$, for a similar effect size of Cohen's $d = 1.34$ in ref.¹⁸ when comparing pre- and post-training thresholds, a sample size of 7 would be required. We used a sample size of 9 for each experiment, with consideration of potential dropout of participants.

Data analysis. The TID thresholds were log-transformed to achieve normal distributions (Shapiro–Wilk test before log-transformation: $p < 0.001$ for auditory and visual TID thresholds; Shapiro–Wilk test after log-transformation: $p = 0.28$ and 0.60 for corresponding TID thresholds). The amount of TID learning or transfer was then measured by the difference of pre- and post-training thresholds in log unit. Data were analyzed with JASP 0.14.1. A two-tailed one-sampled t-test was performed to examine whether a learning or transfer effect was different from 0, and a between-subject ANOVA with Bonferroni's correction was performed for multiple comparisons.

Data availability

Data are available at <https://github.com/visionplusplu/ModalityLearning>.

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Author contributions

Y.-Z.X. and C.Y. designed the experiments. Y.-Z.X. and S.-C.G. conducted the experiments. Y.-Z.X., S.-C.G. and C.Y. analyzed the data and wrote the paper. C.Y. supervised the project.

Competing interest

The authors declare no competing interests.

Additional information

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