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**Precise force controls enhance loudness discrimination of self-generated sound**

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## ABSTRACT

Motor executions alter sensory processes. Studies have shown that loudness perception changes when a sound is generated by active movement. However, it is still unknown where and how the motor-related changes in loudness perception depend on the task demand of motor execution. We examined whether different levels of precision demands in motor control affects loudness perception. We carried out a loudness discrimination test, in which the sound stimulus was produced in conjunction with the force generation task. We tested three target force amplitude levels. The force target was presented on a monitor as a fixed visual target. The generated force was also presented on the same monitor as a movement of the visual cursor. Participants adjusted their force amplitude in a predetermined range without overshooting using these visual targets and moving cursor. In the control condition, the sound and visual stimuli were generated externally (without a force generation task). We found that the discrimination performance was significantly improved when the sound was produced by the force generation task compared to the control condition, in which the sound was produced externally, although we did not find that this improvement in discrimination performance changed depending on the different target force amplitude levels. The

41 results suggest that the demand for precise control to produce a fixed amount of force  
42 may be key to obtaining the facilitatory effect of motor execution in auditory processes.

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44 **Keywords:** auditory perception, auditory-motor interaction, motor execution,  
45 self-generated sound

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## INTRODUCTION

Auditory-motor interaction is important in speech and musical performance (Guenther et al. 1998; Zatorre et al. 2007). In both performances, movement needs to be precisely controlled to generate a target sound, and motor performances are affected by auditory inputs (Pfordresher and Palmer 2006; Houde and Jordan 1998). In addition to auditory processing influencing motor performance, motor performance also influences auditory processing.

The effect of motor execution in auditory processing has been investigated in the context of sensory attenuation of self-generated sounds. Studies involving magnetoencephalography show that the amplitude of auditory event-related responses was attenuated by self-generated sounds compared to externally generated sounds (Aliu et al. 2009; Baess et al. 2011; Martikainen et al. 2005). Indeed, the attenuation of auditory event-related responses has been reported in the processing of speech sounds (Niziolek et al. 2013; Tian and Poeppel, 2010). It is hypothesized that the auditory attenuation that occurs due to motor execution contributes to the distinction between self-produced sensation and sensation due to external reasons by using ‘efference copy’ or ‘corollary discharge’ (i.e., a copy of motor command sent from the motor areas to the sensory areas; Wolpert et al. 1995; Wolpert and Flanagan 2001). In the postulated model,

motor commands are sent to the executing effectors for voluntary movement, and in parallel, an efference copy is sent to the relevant sensory area where sensory signals consequential to the voluntary movement are expected to be received. This copy helps to distinguish between self-generated and externally generated sounds.

Motor executions change the perception of sounds. In speech sound processing, motor execution biases speech perception towards the sound expected from produced speech movements (Sams et al. 2005; Mochida et al. 2013). Niziolek et al. (2013) showed that the attenuation of auditory cortical responses due to participants' speaking was reduced when the generated sound was less prototypical.

The change by motor executions has also been reported in non-speech producing tasks, such as finger movements. Self-generated sounds in a button press task are perceived as less loud compared to externally generated sounds (Sato 2008, Weiss et al. 2011). Reznik et al. (2014) showed that binaural hearing thresholds are lower for self-generated sounds at the near-detection threshold level.

Regarding the interaction between the control of finger force and loudness perception, we empirically acknowledge that applying a stronger force while tapping on a desk or even on a piano key generates a louder sound (Kinoshita et al. 2007). Kunde (2001) found that varying force affects the process of the manual choice reaction task of

loudness perception. This suggests that precise control of the produced force in motor execution may play a role in loudness perception. However, this point is still unclear because the button press task applied in the previous studies does not require precise control of the amplitude of the produced force as long as a button was pressed at a certain level. On the other hand, auditory attenuation can fluctuate depending on movement variability. Neszmélyi and Horváth (2017) demonstrated that auditory event-related potentials in response to self-generated sounds were different among strong and soft pinch fluctuations. This suggests that motor influences on auditory perception may depend on the task context, not simply on the presence or absence of motor execution, but in the ways in which movements (and required force generations) are executed. We thus expect that an explicit control of the produced force in a finger movement for sound production may change loudness perception through auditory-motor interaction.

The current study aimed to examine whether self-generated sounds produced with the adjustment of force amplitude can be processed differently from externally generated sounds and to determine whether the level of precision required by a task affects loudness perception. We carried out experiments using loudness discrimination test with and without a force generation task (Motor and Non-Motor conditions). In



Motor condition, the sound stimulus was produced when the produced force reached the imposed target amplitude. The produced force was presented using a moving cursor, and the target force was presented as a fixed horizontal bar. The participant's task was to adjust the produced force to the target with the visual targets and moving cursor. We tested three different target forces. In Non-Motor condition, the sound was produced externally. We estimated the point of subjective equality (PSE) as a measure of perceptual bias and just noticeable difference (JND) as a measure of discrimination performance. Our prediction was that there would be changes in perceptual bias and/or discrimination performance due to the presence/absence of the force generation task and the amplitude of the target force.

## EXPERIMENT 1

### Methods

#### Participants

Twenty-five healthy students (mean age = 22.1, SD = 2.5 years) participated in Experiment 1. The participants were all right-handed with normal hearing and were

naïve to the purpose of the experiment. The experimental protocols were in accordance with the guidelines set out in the Declaration of Helsinki. All participants signed an informed consent form approved by the Waseda University ethics board.

### **Apparatus, stimuli, and procedure**

The participants were seated in front of a monitor (EV2450, EIZO) with headphones (HD280, Sennheiser). The right hand was gently placed on a desk or a force sensor (USL06-H5-50N-D-FZ, Tec Gihan), and the left hand was placed on a keyboard. The surface of the force sensor was set horizontally on the desk. The force signals from the sensor were amplified and filtered with a 5-Hz low-pass filter in the amplifier (DSA-03A, Tec Gihan). The filtered signals were transferred to a laptop computer via an analog-to-digital converter (NI 9215, National Instruments) with a sampling frequency of 200 Hz. Data acquisition and stimulus presentation were carried out using MATLAB (MathWorks, Inc.) with the Data Acquisition Toolbox (MathWorks, Inc.) and Psychophysics Toolbox extensions (Brainard 1997; Pelli 1997; Kleiner et al. 2007).

*Loudness discrimination test:* Two 1000-Hz sine tones (Fig. 1A) were binaurally presented for 250 ms, separated by an interval of 1000 ms, through the headphones. The participants were asked to indicate whether the second sound was louder or softer than the first sound by pressing the keys on the keyboard with their left hand. The amplitude

of the first sound was fixed at 65 dB in all trials (standard stimulus), and the amplitude of the second sound was varied in each trial (comparison stimulus). We used seven levels of loudness, from 62 dB to 68 dB, in 1-dB increments. The reaction time between the end of the second stimulus and the participant's response was recorded.

*Force generation task for sound presentation:* To generate the sound stimulus, the participants were asked to perform a force generation task, in which they produced a specific amplitude of the force by pressing the force sensor with their right index finger. They were instructed to complete the entire movement to reach the target amplitude and then to release the force in a short period of time (approx. 500 ms). The index finger was positioned slightly above the sensor without touching the start, and returned to the original position at the end of the trial so that the force was completely removed from the sensor at the start and end of each trial. The amplitude of the produced force was reflected in real-time on the monitor as a vertical movement of a cross cursor mark (Fig. 1B). The task was to make the cursor reach the target height presented on the same monitor using a horizontal bar. We also showed the upper limit of the production force (0.5 N larger than the target level) using an additional horizontal bar (Fig. 1B) in order to prevent participants from producing a force level large enough to cover all target amplitudes. The sound stimulus was produced when the peak amplitude of the force was

within the range of the target and the upper limit of the force. The participants practiced before the main experiment, based on the experimenter's instructions, as described below. When the force was produced over the upper limit, the trial was excluded and redone in the following trial.

Experimental procedure: We carried out the loudness discrimination test using two conditions: with the force generation task (Motor condition) and without the task (Non-Motor condition).

In Motor condition, the force generation task was involved in the presentation of the standard stimulus, but not of the comparison stimulus. We tested three levels of target force (1 N, 2 N, and 4 N). In visual instruction, the cursor position was proportional to the change in the force, and hence the height of the target level varied depending on the target force (Fig. 1B).

In Non-Motor condition, participants placed their right hand gently on the desk without any force generation or movement. We replayed the force data recorded in Motor condition to replicate the cursor movement. The standard stimulus was played when the cursor reached the target level on the monitor, as in Motor condition. For this reason, Non-Motor condition was carried out after at least one session of Motor condition was performed.

The experiment consisted of four sessions (two Motor conditions and two Non-Motor conditions), with a 5-minute interval between sessions. In one session, 21 combinations (three target forces  $\times$  seven loudness levels) with eight repetitions were tested in random order (168 trials in total). We carried out two types of session order: 1) Motor condition and Non-Motor condition were alternately tested (alternated pattern), or 2) Motor condition was repeated twice, and then Non-Motor condition was repeated twice (separated pattern). These session orders were counterbalanced among the participants.

Two practice sessions were carried out before the main test to habituate the participants to the force generation task in Motor condition. In these two sessions, the participants practiced using only one level of target force in three levels (1 N, 2 N, or 4 N) for simplification. The number of participants assigned to each level was approximately equal. The first practice session was to practice performing the force generation performance with the visual target in order to produce the standard stimulus described above. In the main test, the standard stimulus was presented when the generated force reached the target amplitude, but not the comparison stimulus. The practice was repeated 30 times. The experimenter verbally instructed and corrected the participants' performance in each trial. The second session involved practicing a sound

discrimination task with the practiced force generation task. The two extreme levels of sound stimulus (62 dB and 68 dB) were used as an example for the comparison stimulus. The participants were asked whether the first or second sound stimulus was louder. Five repetitions in each pair (ten trials in total) were performed in random order. The experimenter verified whether the participants carried out the task and responded correctly.

## **Data analysis**

We calculated the probability that the participants perceived the second sound as being louder for each comparison stimulus. Psychometric functions were obtained by fitting cumulative Gaussians using a maximum-likelihood procedure in Motor and Non-Motor conditions separately. Based on the fitted psychometric curve, we obtained the PSE and the JND. PSE represents the loudness level in which 50% of trials are perceived as louder than the standard. When a participant perceives the first sound as being louder than the second sound, the PSE value becomes larger. If the force generation task in Motor condition modifies the loudness perception of the first sound, the PSE in Motor condition can be changed from that in Non-Motor condition as perceptual bias. JND represents the minimum difference in amplitude due to which a

participant is able to discriminate between the standard and comparison stimuli. JND is defined as half the difference of the comparison tone magnitude judged as louder by 75% and judged as louder on 25% of trials. When the JND value is small, a participant is better able to discriminate between the two sounds. In addition to PSE, JND is also expected to be modified between Motor and Non-Motor conditions. We took averages for each condition on a per-participant basis for the reaction times. PSE, JND, and reaction time were analyzed using a two-way ANOVA with motor factor (Motor condition/ Non-Motor condition) and force factor (1 N, 2 N, and 4 N) as within-participant factors. For post-hoc tests, we applied a simple main effect test when the interaction was observed and applied a Bonferroni correction for the significant main effect of force factor, which had three conditions.

## Results

Fig. 2A shows the JND values for each motor condition across the three task force amplitudes. In JND, the main effect of motor factor was significant ( $F(1, 24) = 16.20$ ,  $p=0.0005$ ;  $\eta^2 = 0.40$ ). In addition, the JND values in Motor condition were smaller than those in Non-Motor condition. We also found a significant main effect of force factor ( $F(2, 48) = 4.00$ ,  $p = 0.0248$ ,  $\eta^2 = 0.14$ ). The JND values significantly increased

as the target force increased. Post-hoc comparisons with Bonferroni correction showed that JNDs in the 4-N condition were significantly larger than in the 1-N ( $p = 0.0104$ ) and 2-N ( $p = 0.0371$ ) conditions. There was no significant interaction between motor factor and force factor ( $F(2, 48) = 0.82, p = 0.4481$ ). In the PSE values (Fig. 2B), we did not find significant differences in all factors: the main effect of motor factor ( $F(1, 24) = 2.06, p = 0.1640$ ), force factor ( $F(2, 48) = 0.51, p = 0.6060$ ), and two-way interaction ( $F(2, 48) = 0.07, p = 0.9367$ ).

We further examined the effect of session order on JND. We carried out three-way ANOVA by adding the factor of session order (alternated pattern and separated pattern) as between-subject factors into the model used in the main analysis. The results showed that the session order factor was not significant ( $F(1, 23) = 0.92, p = 0.3469$ ), while the main significant effect between Motor and Non-Motor conditions ( $F(1, 23) = 17.97, p = 0.0003, \eta^2 = 0.87$ ) and force factor ( $F(2, 46) = 3.91, p = 0.0270, \eta^2 = 0.18$ ) were maintained. There was also a significant interaction between the session order factor and the motor factor ( $F(1, 23) = 4.78, p = 0.0392, \eta^2 = 0.21$ ). In the post-hoc test, the simple-main effect test showed a significant effect of motor factor in the separated pattern group ( $F(1, 23) = 20.65, p = 0.0001, \eta^2 = 0.90$ ), but not in alternated pattern group ( $F(1, 23) = 2.106, p = 0.1603$ ).



The average reaction times across participants were  $779 \text{ ms} \pm 178 \text{ s.e.}$  in Motor condition and  $770 \text{ ms} \pm 213 \text{ s.e.}$  in Non-Motor condition. ANOVA showed no significant difference ( $F(1,24) = 0.28, p = 0.6000$ ) between them. Further, we did not find any significant differences regarding the main effect of force factor ( $F(2, 48) = 0.17, p = 0.8476$ ) or the two-way interaction ( $F(2, 48) = 1.53, p = 0.2284$ ).

In summary, we found that discrimination of sound loudness was improved when the sound was generated by the motor task. We also found that loudness discrimination was improved with a small amplitude of the target force, irrespective of the motor factor. No statistical evidence for differences in perceptual bias was observed. We found no reliable differences in the reaction time.

## **Discussion**

The overall goal of the present study was to examine whether the amplitude of the force produced changes the perceived loudness and discriminability of sounds. Experiment 1 tested this idea using a specific visual situation, in which three levels of target force were presented visually at different heights. We found that generating sound in conjunction with motor execution improved loudness discrimination, but did not bias loudness perception. This finding is consistent with previous studies reporting

improvement in perceptual decisions for self-generated stimuli (Reznik et al., 2014; Myers et al., 2020).

We also found that the discrimination performance was better with smaller target forces. However, the change was similarly observed in both Motor and Non-Motor conditions; therefore, this might not be attributed to the actual force produced in the force generation task. The target forces were represented as three different heights on the monitor in both Motor and Non-Motor conditions. This contextual information based on height might cause similar changes in the two conditions. Thus, we considered this possibility in the next experiment using the same height for the three target force conditions.

## EXPERIMENT 2

We examined whether the observed effect of the target force in Experiment 1 was induced indifferent visual instructions of the target force, in which the height of the visual target was equated.

## Participants

Twenty-five healthy right-handed students with normal hearing participated in the experiment (mean age = 21.5, SD = 3.1 years) and none participated in Experiment 1. All participants were naïve to the purpose of the experiment. The experimental protocols were in accordance with the guidelines set forth in the Declaration of Helsinki and were approved by the Waseda University ethics board. All participants signed approved informed consent forms.

## Methods

The experimental procedure was the same as in Experiment 1, except for the visual presentation used in the force generation task. We applied the same height for all the target force levels (Fig. 1C), resulting in the velocity of cursor movement, given that the produced force varied depending on the target force condition.

## Results

Fig. 3A shows the JND values in Experiment 2. In JND, we found that the main effect of motor factor was significant ( $F(1, 24) = 11.37, p = 0.0025; \eta p^2 = 0.32$ ). The JND values in Motor condition were smaller than those in Non-Motor condition, as seen

in Experiment 1. Contrary to the results obtained in Experiment 1, the main effect in the force factor was not significant ( $F(2, 48) = 0.35, p = 0.7066$ ). We also did not find any interaction effect ( $F(2, 48) = 0.30, p = 0.7413$ ). For PSE values, we did not find any significant difference (Fig. 3B) regarding the main effect of motor factor ( $F(1, 24) = 0.77, p = 0.3865$ ), force factor ( $F(2, 48) = 0.26, p = 0.7699$ ), and the two-way interaction ( $F(2, 48) = 0.99, p = 0.3801$ ).

For the effect of session order in JND values, we carried out three-way ANOVA by including the session order as in Experiment 1. The results showed that there was no significant effect in the session order factor ( $F(1, 23) = 0.05, p = 0.8314$ ), while the main effect between Motor and Non-Motor conditions was maintained. The interaction between the session order factor and the motor factor was not significant ( $F(1,23) = 0.64, p = 0.4338$ ).

The reaction time averaged across participants in Motor condition ( $732 \text{ ms} \pm 105 \text{ s.e.}$ ) was shorter than that in Mon-Motor condition ( $802 \text{ ms} \pm 184 \text{ s.e.}$ ). The main effect of motor factor was significant ( $F(1,24) = 5.35, p = 0.0296, \eta p^2 = 0.05$ ), while the force factor ( $F(2,48) = 0.06, p = 0.9398$ ) and two-way interaction ( $F(2,48) = 1.49, p = 0.2355$ ) were not significant.

In terms of the accuracy of loudness perception, we found consistent improvement in Experiment 1 and Experiment 2. The discrimination performance was better in the force generation task in both experiments. On the other hand, we also found differences in two experiments. We did not find any change in discrimination performance across the target force levels and any difference by session order. Reaction time was different between Motor and Non-Motor conditions, which was not observed in Experiment 1.

## **Discussion**

In Experiment 2, despite the fact that the target height was constant and that the cursor movement velocity was changed, we found consistent results of auditory accuracy between Motor and Non-Motor conditions with those obtained in Experiment 1. The sound generated in conjunction with motor execution improved the performance of loudness discrimination without influencing loudness perception. Unlike Experiment 1, we did not observe modulation of the discrimination performance based on the target force amplitudes. We also obtained different results from Experiment 1 in reaction time and in session order effect. These differences between these two experiments might be due to differences in visual instruction.

## GENERAL DISCUSSION

We found that discrimination performance was significantly improved when the sound stimulus was produced with the force generation task compared to when the sound stimulus was produced externally, whereas perceptual bias did not change between with and without the force generation task. Since the results were consistent in all three force target conditions and different visual instructions between Experiment 1 and Experiment 2, the task requirement to produce a specific amount of finger force, compared to a simple button pressing action without any requirement of force control, can play an important role in enhancing loudness discrimination. Although we expected that this enhancement would change depending on the target of force production, we did not find the expected tendency in the current experimental situation.

In addition to this enhancement effect, the response pattern across the target force amplitudes was also modified by the use of visual instructions. Improved loudness discrimination was found in the case of the smaller target force in both Motor and Non-Motor conditions in Experiment 1, while discrimination performance was not significantly different among the target force amplitudes in Experiment 2. The difference between Experiment 1 and 2 was also seen in the reaction time data and in session order analysis. These results suggest that visual representation of the target force

can influence the relationship between the force generation task and the loudness discrimination.

Auditory processing of self-generated sounds has been frequently investigated in the context of sensory attenuation. Previous studies demonstrated attenuated responses to self-generated stimuli compared with otherwise identical sensory stimuli perceived in a passive manner (Blakemore et al. 1998; Martikainen et al. 2004; Aliu et al. 2009; Baess et al. 2009; Horváth 2014; Timm et al. 2014). In these studies, it was hypothesized that the processing of self-generated sounds can be attenuated to distinguish between self-generated and externally generated sounds. These attenuated responses have been frequently considered as a reduction in sensitivity of sensory processing, but rather indicate an increase in sensitivity (e.g., Eliades and Wang 2003). In the auditory-motor interaction, the previous studies showed that motor commands and corresponding somatosensory inputs can facilitate auditory processing (Reznik et al., 2014; Morillon et al, 2015). Myers et al. (2020) suggested that sensorimotor integration facilitates auditory discrimination. Our findings are consistent with the facilitation of auditory discrimination with motor execution; however, the mechanisms responsible for this relationship may change depending on the context of the auditory-motor interaction tasks. Indeed, context dependency has already been reported by Reznik et al. (2015).

When different auditory contexts were tested using sounds proximal to and larger than the threshold level, the loudness perception changed depending on the sound characteristics, even though the sound stimuli were produced with the same motor task.

In the current task involving the force sensor being pressed with the index finger, the specific force amplitude was achieved by adjusting a moving cursor to the visual target. Neszmélyi and Horváth (2017) showed an attenuation effect using a similar type of force generation task. However, their task was to go over a specific threshold level, while our task required the participants to reach a specific force amplitude without exceeding a certain limit. This constraint necessitated more precise control of the force amplitude, which may be key to inducing a facilitatory effect in auditory-motor interactions.

It is possible that the prediction of sound timing and the difference in attention level play a role in the changes in discrimination performance between Motor and Non-Motor conditions. As for the stimulus presentation, the participants could easily predict the timing of sound presentation in Motor condition, since the sound was caused by the participants' motor execution. However, the sound timing could also be predicted in Non-Motor condition by observing the moving cursor reaching the target line. Given that motor prediction and visual prediction are similar (Kaiser et al. 2018, see Weiss and



Schütz-Bosbach, 2012), a prediction mechanism would contribute similarly to both Motor and Non-Motor conditions. Attentional factors might also change depending on the involvement of the force generation task. In general, imposing an additional task while performing a main task disturbs the performance of the main task. In the current experiments, it was expected that the participants would display greater attention to the auditory task in Non-Motor condition. This is consistent with the participants' impressions in the post-experiment interviews. Most of the participants reported that they felt it easier to focus on listening to the sound stimulus in Non-Motor condition than in Motor condition. Despite this, the discrimination performance was better in Motor condition. Thus, the attentional factor may not be involved in the current change in loudness discrimination. This idea may also be supported by the inconsistent result of reaction time between the two experiments. A difference between Motor and Non-Motor conditions was found in Experiment 1, but not in Experiment 2, suggesting that attentional level between Motor and Non-Motor condition may be different in the two experiments. Thus, the differences in prediction and attention between Motor and Non-Motor conditions cannot explain the improvement in loudness discrimination in the force generation task.

We hypothesized that auditory processing may change depending on the level of fine controls required for performing a motor task, due to interactions between voluntary command, somatosensory, and audition. Macefield et al. (1996) investigated the adjustment of gripping force by two fingers based on skin sensation signals on the fingertip, and suggested that smaller force generation might require more sensitive sensory input feedback. In the current test, finer somatosensory signals may be required for force generation with 1 N and 2 N, compared to 4 N. Despite this expectation, we did not find any reliable interaction between motor factor and force factor in either Experiment 1 or 2. In the current context, the loudness perception may not be changed according to the amplitude of the produced force.

The main limitation of the present study was that the visual presentation was used for the instruction of the target force amplitude. It was difficult to completely eliminate additional information concerning the differences across the tasks. In Experiment 1, the three target forces were represented by displaying the visual target at different heights. In Experiment 2, while we removed the difference in height, the velocity of the moving cursor varied depending on the target force. The difference in visual instruction induced changes in loudness discrimination. In Experiment 1, the smaller force amplitude (which coincides with the lower height of the visual target) led to improved

discrimination performance. This tendency was not observed in Experiment 2, in which the loudness discrimination was similar among the three target force amplitudes. This difference in visual instruction might also affect reaction time since the result of reaction time was not consistent in the two experiments. The participants responded quicker in Motor condition in Experiment 2, but their responses were not different between Motor and Non-Motor condition in Experiment 1. This suggests that visual instruction or presentation affects the overall performance of the loudness discrimination task. Note that the current visual instructions did not affect the achievement of the force generation task because all participants were able to produce the sound successfully without overshooting a predetermined range of task force amplitude. Regardless of the difference in visual instruction, we found improved loudness discrimination for the self-generated sounds compared to the externally generated sounds. Since the effects of visual instruction were consistent in both Motor and Non-Motor conditions, we concluded that this visual effect can be a separate effect from the current motor effect in auditory perception. We did not pursue this visual effect further in the current study because our purpose is to investigate the motor effect on auditory perception alone.

Another limitation concerns the order of the experimental sessions. In the current procedure, we carried out at least one Motor condition before Non-Motor condition in order to replay the visual presentation of Motor condition in Non-Motor condition. This limitation of session order may have caused the current results in loudness discrimination. Considering this order effect, we carried out two session orders (alternated pattern and separated pattern). The main difference between these two session orders was that the 2nd session and 3rd sessions were switched. The separated pattern may thereby induce a larger effect than the alternated pattern. Three-way ANOVA with session order (alternated pattern and separated pattern) as a factor showed this tendency in Experiment 1 but not in Experiment 2. This inconsistent result of session order between the two experiments suggests that session order may not be related to the main finding, that is, the improvement of loudness discrimination ability between Motor and Non-Motor conditions was consistently induced in two experiments.

To conclude, the current findings support the hypothesis that during sound-producing actions, motor executions modify sensory processing. The auditory-motor interaction required to produce a fixed amount of force might be related to discrimination of auditory consequences by our own movements, such as speaking and playing a musical instrument.

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## Figure Legends

Fig. 1. Experimental procedure. A) Temporal patterns of auditory stimulation (top) and trajectory of finger force generation with three different target amplitudes (bottom). B) Examples of visual presentation in Experiment 1. The cross mark represents the cursor of the force amplitude. The two horizontal lines represent the target amplitude (bottom line) and upper limit (top line). C) Example of visual presentation in Experiment 2 as in B.

Fig. 2. Mean values of A) just-noticeable difference (JND) and B) point of subjective equality (PSE) in Experiment 1. The solid line with filled circles represents Motor condition, and the dashed line with open circles represents Non-Motor condition. The small dots represent responses in each individual participant. Error bars show the standard error among the participants. PSE is represented as a value relative to 65 dB.

Fig. 3. A) Mean values of A) just-noticeable difference (JND) and B) point of subjective equality (PSE) in Experiment 2. The solid line with filled circles represents Motor condition, and the dashed line with open circles represents Non-Motor condition.

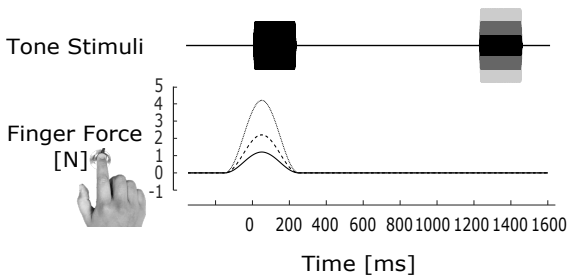
580        The small dots represent responses in each individual participant. Error bars show  
581        the standard error across the participants. PSE is represented as a value relative to  
582        65 dB.

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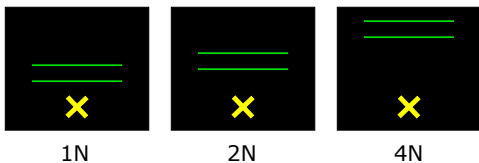
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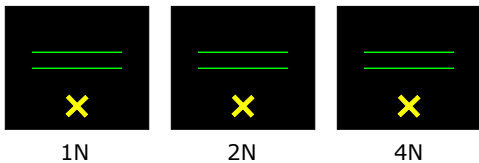
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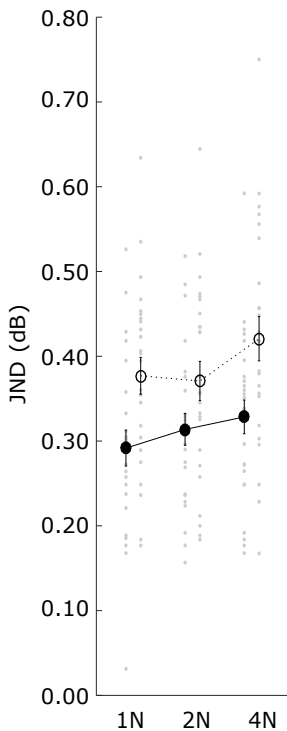
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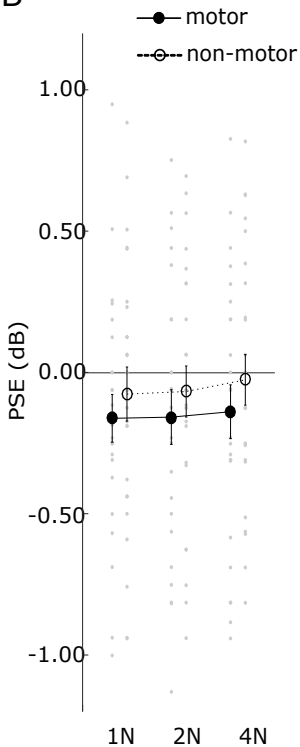
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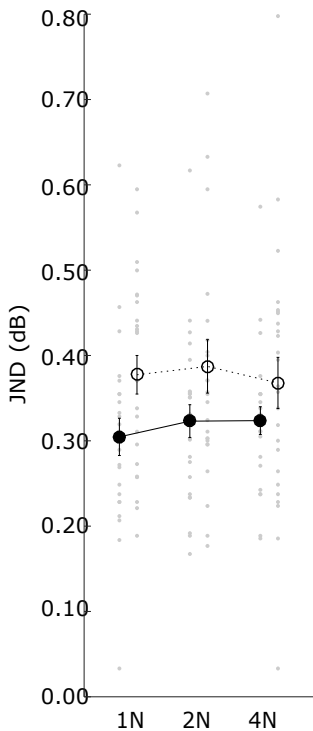
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A



B

