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

2

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17

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ABSTRACT

25 Motor executions alter sensory processes. Studies have shown that loudness perception
26 changes when a sound is generated by active movement. However, it is still unknown
27 where and how the motor-related changes in loudness perception depend on the task
28 demand of motor execution. We examined whether different levels of precision
29 demands in motor control affects loudness perception. We carried out a loudness
30 discrimination test, in which the sound stimulus was produced in conjunction with the
31 force generation task. We tested three target force amplitude levels. The force target was
32 presented on a monitor as a fixed visual target. The generated force was also presented
33 on the same monitor as a movement of the visual cursor. Participants adjusted their
34 force amplitude in a predetermined range without overshooting using these visual
35 targets and moving cursor. In the control condition, the sound and visual stimuli were
36 generated externally (without a force generation task). We found that the discrimination
37 performance was significantly improved when the sound was produced by the force
38 generation task compared to the control condition, in which the sound was produced
39 externally, although we did not find that this improvement in discrimination
40 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.

43

44 **Keywords:** auditory perception, auditory-motor interaction, motor execution,

45 self-generated sound

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48

INTRODUCTION

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

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

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

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

75 The change by motor executions has also been reported in non-speech producing
76 tasks, such as finger movements. Self-generated sounds in a button press task are
77 perceived as less loud compared to externally generated sounds (Sato 2008, Weiss et al.
78 2011). Reznik et al. (2014) showed that binaural hearing thresholds are lower for
79 self-generated sounds at the near-detection threshold level.

80 Regarding the interaction between the control of finger force and loudness
81 perception, we empirically acknowledge that applying a stronger force while tapping on
82 a desk or even on a piano key generates a louder sound (Kinoshita et al. 2007). Kunde
83 (2001) found that varying force affects the process of the manual choice reaction task of

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

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

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

112

113

114

115

EXPERIMENT 1

116 **Methods**

117 **Participants**

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

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

123 **Apparatus, stimuli, and procedure**

124 The participants were seated in front of a monitor (EV2450, EIZO) with
125 headphones (HD280, Sennheiser). The right hand was gently placed on a desk or a force
126 sensor (USL06-H5-50N-D-FZ, Tec Gihan), and the left hand was placed on a keyboard.

127 The surface of the force sensor was set horizontally on the desk. The force signals from
128 the sensor were amplified and filtered with a 5-Hz low-pass filter in the amplifier
129 (DSA-03A, Tec Gihan). The filtered signals were transferred to a laptop computer via
130 an analog-to-digital converter (NI 9215, National Instruments) with a sampling
131 frequency of 200 Hz. Data acquisition and stimulus presentation were carried out using
132 MATLAB (MathWorks, Inc.) with the Data Acquisition Toolbox (MathWorks, Inc.) and
133 Psychophysics Toolbox extensions (Brainard 1997;Pelli 1997; Kleiner et al. 2007).

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

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

142 *Force generation task for sound presentation:* To generate the sound stimulus, the
143 participants were asked to perform a force generation task, in which they produced a
144 specific amplitude of the force by pressing the force sensor with their right index finger.
145 They were instructed to complete the entire movement to reach the target amplitude and
146 then to release the force in a short period of time (approx. 500 ms). The index finger
147 was positioned slightly above the sensor without touching the start, and returned to the
148 original position at the end of the trial so that the force was completely removed from
149 the sensor at the start and end of each trial. The amplitude of the produced force was
150 reflected in real-time on the monitor as a vertical movement of a cross cursor mark (Fig.
151 1B). The task was to make the cursor reach the target height presented on the same
152 monitor using a horizontal bar. We also showed the upper limit of the production force
153 (0.5 N larger than the target level) using an additional horizontal bar (Fig. 1B) in order
154 to prevent participants from producing a force level large enough to cover all target
155 amplitudes. The sound stimulus was produced when the peak amplitude of the force was

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

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

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

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

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

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

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

198

199 **Data analysis**

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

210 participant is able to discriminate between the standard and comparison stimuli. JND is
211 defined as half the difference of the comparison tone magnitude judged as louder by
212 75% and judged as louder on 25% of trials. When the JND value is small, a participant
213 is better able to discriminate between the two sounds. In addition to PSE, JND is also
214 expected to be modified between Motor and Non-Motor conditions. We took averages
215 for each condition on a per-participant basis for the reaction times. PSE, JND, and
216 reaction time were analyzed using a two-way ANOVA with motor factor (Motor
217 condition/ Non-Motor condition) and force factor (1 N, 2 N, and 4 N) as
218 within-participant factors. For post-hoc tests, we applied a simple main effect test when
219 the interaction was observed and applied a Bonferroni correction for the significant
220 main effect of force factor, which had three conditions.

221

222 **Results**

223 Fig. 2A shows the JND values for each motor condition across the three task force
224 amplitudes. In JND, the main effect of motor factor was significant ($F(1, 24) = 16.20$,
225 $p=0.0005$; $\eta p^2 = 0.40$). In addition, the JND values in Motor condition were smaller
226 than those in Non-Motor condition. We also found a significant main effect of force
227 factor ($F(2, 48) = 4.00$, $p = 0.0248$, $\eta p^2 = 0.14$). The JND values significantly increased

228 as the target force increased. Post-hoc comparisons with Bonferroni correction showed
229 that JNDs in the 4-N condition were significantly larger than in the 1-N ($p= 0.0104$) and
230 2-N ($p =0.0371$) conditions. There was no significant interaction between motor factor
231 and force factor ($F(2, 48) = 0.82, p = 0.4481$). In the PSE values (Fig. 2B), we did not
232 find significant differences in all factors: the main effect of motor factor ($F(1, 24) =$
233 $2.06, p = 0.1640$), force factor ($F(2, 48) = 0.51, p = 0.6060$), and two-way interaction
234 ($F(2, 48) = 0.07, p = 0.9367$).

235 We further examined the effect of session order on JND. We carried out three-way
236 ANOVA by adding the factor of session order (alternated pattern and separated pattern)
237 as between-subject factors into the model used in the main analysis. The results showed
238 that the session order factor was not significant ($F(1, 23) = 0.92, p = 0.3469$), while the
239 main significant effect between Motor and Non-Motor conditions ($F(1, 23) = 17.97, p =$
240 $0.0003, \eta^2 = 0.87$) and force factor ($F(2,46) = 3.91, p = 0.0270, \eta^2 = 0.18$) were
241 maintained. There was also a significant interaction between the session order factor
242 and the motor factor ($F(1,23) = 4.78, p = 0.0392, \eta^2 = 0.21$). In the post-hoc test, the
243 simple-main effect test showed a significant effect of motor factor in the separated
244 pattern group ($F(1,23) = 20.65, p = 0.0001, \eta^2 = 0.90$), but not in alternated pattern
245 group ($F(1,23) = 2.106, p = 0.1603$).

246 The average reaction times across participants were 779 ms± 178 s.e. in Motor
247 condition and 770 ms± 213 s.e. in Non-Motor condition. ANOVA showed no significant
248 difference ($F(1,24) = 0.28$, $p = 0.6000$) between them. Further, we did not find any
249 significant differences regarding the main effect of force factor ($F(2, 48) = 0.17$, $p =$
250 0.8476) or the two-way interaction ($F(2, 48) = 1.53$, $p = 0.2284$).

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

256

257 **Discussion**

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

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

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

274

275

276

277

EXPERIMENT 2

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

281

282 **Participants**

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

289

290 **Methods**

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

295

296 **Results**

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

300 in Experiment 1. Contrary to the results obtained in Experiment 1, the main effect in the
301 force factor was not significant ($F(2, 48) = 0.35, p = 0.7066$). We also did not find any
302 interaction effect ($F(2, 48) = 0.30, p = 0.7413$). For PSE values, we did not find any
303 significant difference (Fig. 3B) regarding the main effect of motor factor ($F(1, 24) =$
304 $0.77, p = 0.3865$), force factor ($F(2, 48) = 0.26, p = 0.7699$), and the two-way
305 interaction ($F(2, 48) = 0.99, p = 0.3801$).

306 For the effect of session order in JND values, we carried out three-way ANOVA by
307 including the session order as in Experiment 1. The results showed that there was no
308 significant effect in the session order factor ($F(1, 23) = 0.05, p = 0.8314$), while the
309 main effect between Motor and Non-Motor conditions was maintained. The interaction
310 between the session order factor and the motor factor was not significant ($F(1,23) =$
311 $0.64, p = 0.4338$).

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

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

323

324 **Discussion**

325 In Experiment 2, despite the fact that the target height was constant and that the
326 cursor movement velocity was changed, we found consistent results of auditory
327 accuracy between Motor and Non-Motor conditions with those obtained in Experiment
328 1. The sound generated in conjunction with motor execution improved the performance
329 of loudness discrimination without influencing loudness perception. Unlike Experiment
330 1, we did not observe modulation of the discrimination performance based on the target
331 force amplitudes. We also obtained different results from Experiment 1 in reaction time
332 and in session order effect. These differences between these two experiments might be
333 due to differences in visual instruction.

334

335

GENERAL DISCUSSION

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

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

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

355 Auditory processing of self-generated sounds has been frequently investigated in
356 the context of sensory attenuation. Previous studies demonstrated attenuated responses
357 to self-generated stimuli compared with otherwise identical sensory stimuli perceived in
358 a passive manner (Blakemore et al. 1998; Martikainen et al. 2004; Aliu et al. 2009;
359 Baess et al. 2009; Horváth 2014; Timm et al. 2014). In these studies, it was
360 hypothesized that the processing of self-generated sounds can be attenuated to
361 distinguish between self-generated and externally generated sounds. These attenuated
362 responses have been frequently considered as a reduction in sensitivity of sensory
363 processing, but rather indicate an increase in sensitivity (e.g., Eliades and Wang 2003).
364 In the auditory-motor interaction, the previous studies showed that motor commands
365 and corresponding somatosensory inputs can facilitate auditory processing (Reznik et al.,
366 2014; Morillon et al, 2015). Myers et al. (2020) suggested that sensorimotor integration
367 facilitates auditory discrimination. Our findings are consistent with the facilitation of
368 auditory discrimination with motor execution; however, the mechanisms responsible for
369 this relationship may change depending on the context of the auditory-motor interaction
370 tasks. Indeed, context dependency has already been reported by Reznik et al. (2015).

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

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

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

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

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

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

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

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

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

459

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561

562 **Figure Legends**

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

569

570 Fig. 2. Mean values of A) just-noticeable difference (JND) and B) point of subjective
571 equality (PSE) in Experiment 1. The solid line with filled circles represents Motor
572 condition, and the dashed line with open circles represents Non-Motor condition.
573 The small dots represent responses in each individual participant. Error bars show
574 the standard error among the participants. PSE is represented as a value relative to
575 65 dB.

576

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

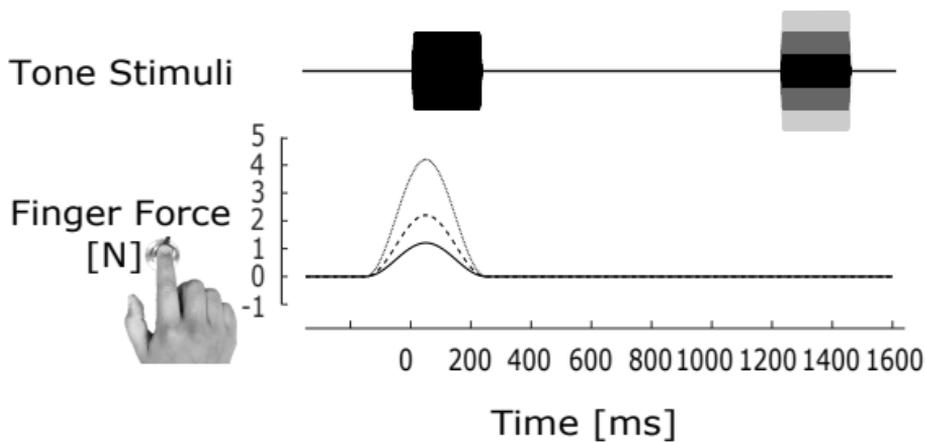
580 The small dots represent responses in each individual participant. Error bars show
581 the standard error across the participants. PSE is represented as a value relative to
582 65 dB.

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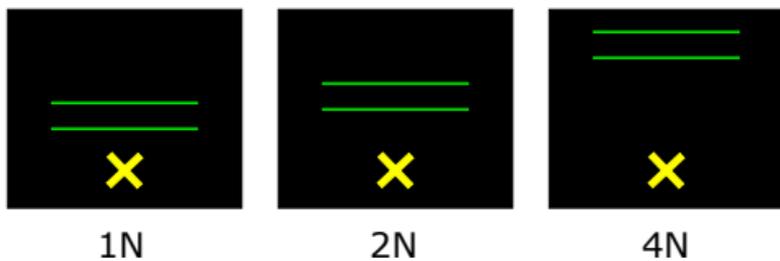
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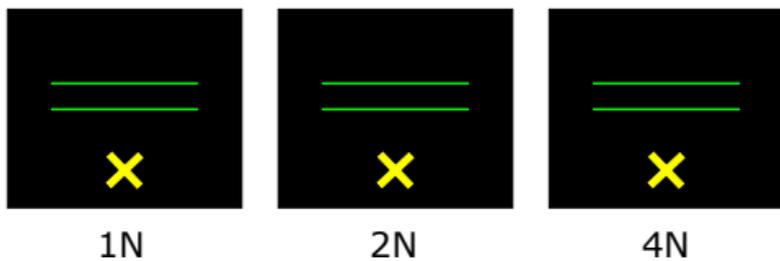
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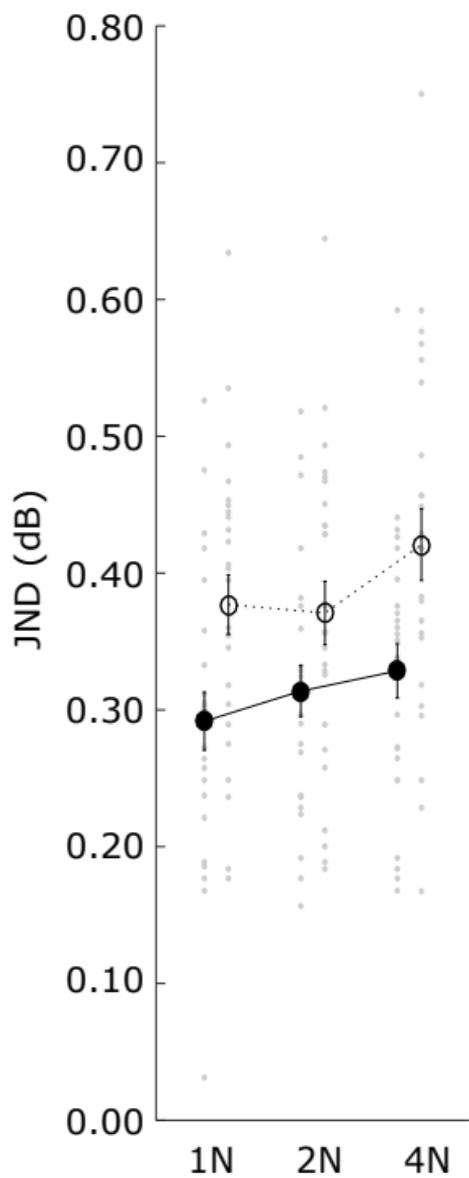
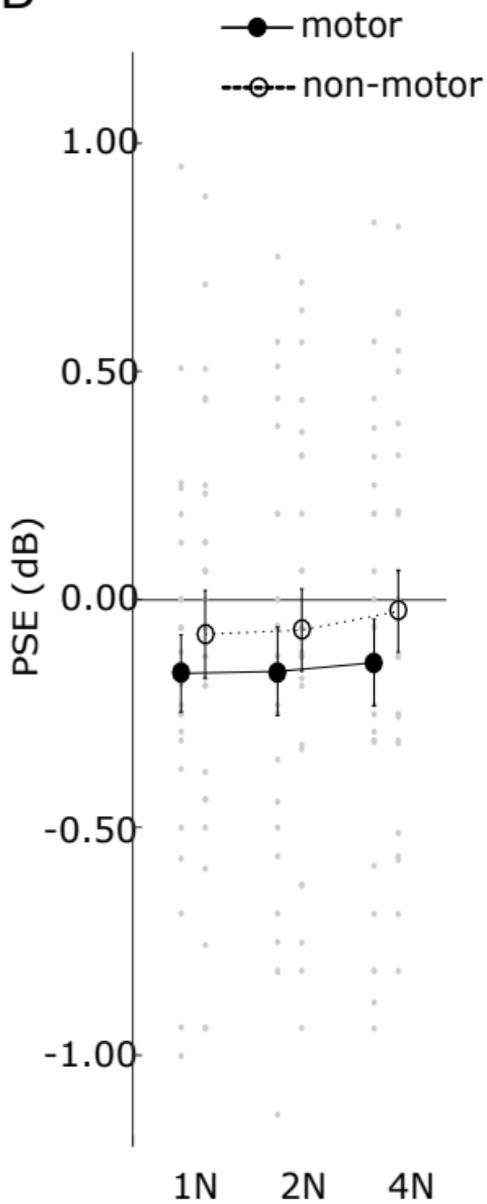


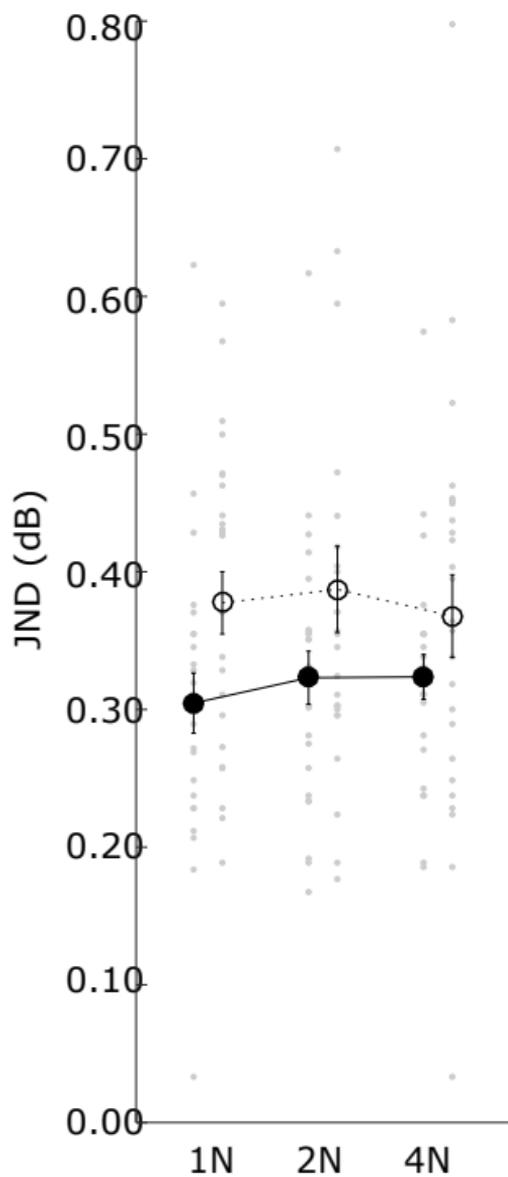
B



C



A**B**

A**B**