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1 **Self-generation and sound intensity interactively modulate**  
2 **perceptual bias, but not perceptual sensitivity**

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26 **Highlights**

- 27 ● Self-generation and stimulus intensity interactively shape auditory perception.
- 28 ● Supra-threshold self-generated sounds are perceptually attenuated.
- 29 ● When near-threshold, perceived intensity is enhanced for self-generated sounds.
- 30 ● Self-generation and intensity modulate perceptual bias, rather than sensitivity.
- 31 ● Surprise-driven attentional mechanisms may underlie these perceptual shifts.

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32 **Abstract**

33 The ability to distinguish self-generated stimuli from those caused by external sources is  
34 critical for all behaving organisms. Although many studies point to a sensory attenuation of  
35 self-generated stimuli, recent evidence suggests that motor actions can result in either  
36 attenuated or enhanced perceptual processing depending on the environmental context (i.e.,  
37 stimulus intensity). The present study employed 2-AFC sound detection and loudness  
38 discrimination tasks to test whether sound source (self- or externally-generated) and  
39 stimulus intensity (supra- or near-threshold) interactively modulate detection ability and  
40 loudness perception. Self-generation did not affect detection and discrimination sensitivity  
41 (i.e., detection thresholds and Just Noticeable Difference, respectively). However, in the  
42 discrimination task, we observed a significant interaction between self-generation and  
43 intensity on perceptual bias (i.e. Point of Subjective Equality). Supra-threshold self-  
44 generated sounds were perceived softer than externally-generated ones, while at near-  
45 threshold intensities self-generated sounds were perceived louder than externally-generated  
46 ones. Our findings provide empirical support to recent theories on how predictions and  
47 signal intensity modulate perceptual processing, pointing to interactive effects of intensity  
48 and self-generation that seem to be driven by a biased estimate of perceived loudness,  
49 rather by changes in detection and discrimination sensitivity.

50 *Keywords:* self-generation, attenuation, psychophysics, auditory processing

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## 51 **1. Introduction**

52           The ability to make sense of the noisy information present in the world around us is  
53 crucial for our survival. Yet, what we perceive is not a veridical reproduction of the signals  
54 reaching our sensory apparatus, but it is instead an interplay between bottom-up processes  
55 and top-down predictions about the upcoming events (Friston, 2005). Forming predictions  
56 about what is about to come helps us interact with the world around us, by perceptually  
57 prioritizing behaviourally relevant sensory events. Attempts to assess how expectations  
58 influence our perception show that we are more likely to report perceiving an expected than  
59 an unexpected stimulus (Chalk et al., 2010; Jaramillo & Zador, 2011; Pinto et al., 2015;  
60 Stein & Peelen, 2015; Wyart et al., 2012). However, although the facilitatory effects of  
61 expectation on perceptual processing have been found in the wider sensory literature, they  
62 usually conflict with work from the action domain (for a recent review see Press et al.,  
63 2020).

64           Being able to predict the sensory consequences of our own action constitutes a  
65 specific instance of predictive processing that is highly critical in perceiving behaviourally  
66 relevant events in our environment. Several lines of research have shown that actions  
67 suppress the processing of the self-generated reafferent input (e.g., action-induced  
68 blindness, Kunde & Wühr, 2004; saccadic suppression, Ross et al., 2001; self-generation of  
69 stimuli, Straka et al., 2018). The attenuated physiological responses to self- compared to  
70 externally-generated inputs appear to be widespread throughout the animal kingdom and  
71 modality independent, being reported in a wide range of species (Chagnaud et al., 2015;  
72 Kelley & Bass, 2010; Kim et al., 2015; Requarth & Sawtell, 2011; Roy & Cullen, 2001;  
73 Schneider et al., 2014) and in several sensory modalities, including the auditory (Baess et

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74 al., 2011; Horváth, 2013a, 2013b; Martikainen et al., 2005; Mifsud et al., 2017; SanMiguel  
75 et al., 2013; Saupe et al., 2013; Schafer & Marcus, 1973; Timm et al., 2013), visual  
76 (Hughes & Waszak, 2011; Mifsud et al., 2018; Roussel et al., 2013, 2014), and tactile  
77 (Blakemore et al., 1998; Hesse et al., 2010; Kilteni et al., 2020). An influential proposal  
78 referred to as the ‘cancellation account’ attributes sensory attenuation to an efference copy  
79 of the motor command generated before or during an action that is sent from the motor to  
80 the corresponding sensory cortices (Sperry, 1950; von Holst, 1954). This efference copy  
81 allows one to accurately predict the imminent stimulation resulting from the individual’s  
82 own action via internal forward modelling (Wolpert et al., 1995). The resulting motor-  
83 driven predictions of sensory reafference (i.e., the “corollary discharge”) are then compared  
84 to the actual sensory consequences of one’s actions, and subsequently, only the difference  
85 between the two (i.e., prediction error) is sent to higher stages of the neuronal hierarchy for  
86 further processing (Friston, 2005; Wolpert & Miall, 1996), effectively cancelling out  
87 responses to predictable input. The cancelling role of the motor-driven predictions in  
88 sensory cortices has been suggested to be of great ecological importance, as it contributes  
89 in prioritizing the newsworthy unpredictable information (Barron et al., 2020), by  
90 distinguishing stimuli that correspond to potentially biologically significant external events  
91 from stimuli that arise simply as a consequence of our own motor actions (Blakemore et al.,  
92 2000; Poulet & Hedwig, 2002), and shapes our perception of sense of agency (Gallagher,  
93 2000).

94           However, in the animal kingdom corollary discharge has been found to influence  
95 sensory processing in myriad ways besides cancellation of reafference (Crapse & Sommer,  
96 2008). Contrary to cancellation theories, recent sharpening models propose that perception

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97 is biased towards the expected input (e.g., Yon & Press, 2017; Yon et al., 2020), in line  
98 with evidence showing enhanced BOLD responses to self-generated stimuli (e.g., Reznik et  
99 al., 2014; Simões-Franklin et al., 2011) and increased discharges in some neurons during  
100 self-initiated vocalizations (Eliades & Wang, 2003). The discrepancy between cancellation  
101 and sharpening accounts is also reflected in human studies attempting to assess the  
102 behavioural correlates of the neurophysiological effects of self-generation on stimulus  
103 processing. While self-initiated action effects have been typically found to be perceived as  
104 less ticklish (e.g., Blakemore et al., 1998; Claxton, 1975; Weiskrantz et al., 1971), less  
105 forceful (Bays et al., 2005; Kilteni et al., 2020), or less loud (Sato, 2008; Weiss et al.,  
106 2011a, 2011b) than equivalent stimuli initiated by another person or by a computer, recent  
107 findings show enhanced perception for action-expected outcomes (Desantis et al., 2016;  
108 Reznik et al., 2014; Yon et al., 2020). Collectively, the discrepancy in the results reported  
109 so far points to factors other than self-generation that may interactively modulate sensory  
110 processing during motor actions.

111 In a closer look, the mixed findings reported so far as concerns the  
112 neurophysiological and behavioural effects of motor predictions on sensory processing may  
113 be due to critical differences in the experimental paradigm, stimulus features, and obtained  
114 measures (see Table 1 for a summary of the human studies with auditory stimuli). On the  
115 one hand, animal studies with perceptual measures have reported both attenuation  
116 (McGinley et al., 2015; Neske et al., 2019) and enhancement (Carcea et al., 2017), but  
117 assess perceptual processing during locomotion compared to quiescence (Bennett et al.,  
118 2018; McGinley et al., 2015; Neske et al., 2019) or in Go compared to NoGo trials (Carcea  
119 et al., 2017). However, sensory processing during action may differ from processing of

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120 stimuli resulting from action as assessed in contingent paradigms with humans that  
121 typically compare action-predicted vs. unpredictable stimuli (i.e., self- vs. externally-  
122 generated; e.g., Sato, 2008; Kilteni et al., 2020; Weiss et al., 2011a, 2011b) or predicted vs.  
123 mispredicted stimuli (action-congruent vs. action-incongruent; e.g., Yon et al., 2020; Yon  
124 & Press, 2017), thus rendering it difficult to disentangle whether the observed effects are  
125 driven by specific motor-driven predictions or by unspecific arousal mechanisms  
126 (McGinley et al., 2015). Additionally, studies also differ in the task and stimulus intensities  
127 that they employ. Human studies reporting suppression typically use supra-threshold  
128 stimuli in discrimination paradigms and show modulations in perceptual bias (Point of  
129 Subjective Equality; PSE) rather than sensitivity measures (Just Noticeable Difference;  
130 JND, e.g., Sato, 2008; Kilteni et al., 2020; Weiss et al., 2011a, 2011b). In contrast, evidence  
131 supporting sharpening accounts has been reported mostly in detection paradigms that  
132 obligatorily need to use near-threshold stimuli (Cao & Gross, 2015; Desantis et al., 2016;  
133 Reznik et al., 2014; Yon et al., 2020; Yon & Press, 2017). This line of work has reported  
134 changes in sensitivity in both directions (e.g., Reznik et al., 2014; Cardoso-Leite et al.,  
135 2010; Cao & Gross, 2015, but see Schwartz et al., 2018 for no effects), but also in decision  
136 processes (Desantis et al., 2016; Yon et al., 2020). Collectively, these findings raise the  
137 possibility that the conflicting findings on the nature of the effects of action on the  
138 perceptual processing of self-initiated stimuli may depend on a handful of specific factors  
139 (i.e., action/no action comparisons vs. action-predicted/action-unpredicted comparisons;  
140 stimulus intensity) that may selectively affect certain aspects of perception (i.e., detection  
141 or discrimination ability; sensitivity or bias).

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143 Table 1

144 *Human studies assessing the behavioural effects of self-generation on auditory processing.*

<b>Self-generation effects</b>	<b>Study</b>	<b>Task</b>	<b>Intensity</b>	<b>Bias / sensitivity</b>
Attenuation	Sato, 2008; Weiss et al., 2011a, 2011b	Loudness discrimination	L	Bias (PSE)
	Reznik et al., 2015			Bias (% 1 <sup>st</sup> sound louder)
	Cao & Gross, 2015	Detection of attended frequencies	NT	Sensitivity (d')
Enhancement	Reznik et al., 2015	Loudness discrimination	NT	Bias (% 1 <sup>st</sup> sound louder)
	Reznik et al., 2014	Detection	NT	Sensitivity (d', thresholds)
	Myers et al., 2020	Loudness discrimination	L	Sensitivity (% correct)
No effect	Sato, 2008; Weiss et al., 2011a, 2011b	Loudness discrimination	L	Sensitivity (JND)
	Myers et al., 2020	Detection	NT	Sensitivity (thresholds)
	Cao & Gross, 2015	Detection of nonattended frequencies	NT	Sensitivity (d')

145 *Note.* Studies have reported either attenuation, enhancement, or no effects in detection or  
 146 discrimination tasks with either loud (L) or near-threshold (NT) sounds by obtaining  
 147 various measures that are used as a proxy of either bias or sensitivity (Point of Subject  
 148 Equality, PSE; Just Noticeable Difference, JND; d', d-prime).

149

150 Recent work has indeed provided some evidence showing that sensory attenuation  
 151 may be dependent on the stimulus intensity (Burin et al., 2017; Reznik et al., 2015). Reznik  
 152 and colleagues (2015) had participants judge the perceived intensity of self- and externally-  
 153 generated sounds presented at a supra- or a near-threshold intensity. Unbeknownst to the  
 154 participants, the two sounds were always presented at the exact same intensity, but they



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155 were asked to report which one of them was louder. Their results showed a significant  
156 interaction between intensity and sound source. While the supra-threshold self-generated  
157 sounds were perceived as less loud than the passive comparisons, the opposite effect was  
158 obtained for near-threshold intensities. That is, when the sensory consequences of  
159 participants' movements were of low intensity, a significant sensory enhancement was  
160 observed, with the self-generated tones being judged as louder than the comparison passive  
161 tones. However, due to the experimental design of this study (i.e., no varying comparison  
162 intensities), no psychophysical measures (e.g., PSE or JND) could be obtained to further  
163 examine whether the modulatory effects of intensity on perceptual processing for self-  
164 initiated sounds are driven by changes in bias or sensitivity, respectively.

165         Taken together, the evidence reported so far suggests that the direction of self-  
166 generation effects may be dependent on the intensity and therefore the amount of sensory  
167 noise in the signal. Indeed, recent work has highlighted the role of sensory noise in driving  
168 perceptual processing, suggesting that enhanced sensory processing for unexpected events  
169 is dependent on the 'newsworthiness' of the signal, such that the less the sensory noise (i.e.,  
170 high intensities), the higher the sensory precision of the signal, and thus the more  
171 informative the unexpected (i.e., externally-generated) stimulus (Press et al., 2020; Barron  
172 et al., 2020). Yet, we reason that the findings obtained from the previous self-generation  
173 studies cannot provide solid conclusions on this matter, due to the use of a small range of  
174 intensities (either supra-threshold only; Sato, 2008; Weiss et al., 2011a, 2011b, near-  
175 threshold only; Reznik et al., 2014, or only one of each; Reznik et al., 2015). More  
176 importantly, the inconsistency between the studies conducted so far raises the possibility of  
177 differential effects of self-generation on different aspects of perceptual processing. Indeed,

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178 expectations have been found to yield differential effects on perceptual bias and sensitivity  
179 measures in the literature outside the action domain (e.g., Bang & Rahnev, 2017; Wyart et  
180 al., 2012). However, no systematic attempts have been made to date to assess whether  
181 motor actions alter our sensitivity to the sensory feedback or whether they result in a biased  
182 estimate of its perceived loudness.

183         The aim of the present study is twofold: We sought to elucidate the modulatory  
184 effects of intensity on the perceptual processing of self-generated sounds across the  
185 auditory intensity range, while systematically assessing whether the expected effects drive  
186 changes in perceptual sensitivity and/or perceptual bias. To this end, we employed a sound  
187 detection and a loudness discrimination task and compared the detection and discrimination  
188 sensitivity, as well as the possible bias in perceived loudness for self- vs. externally-  
189 generated sounds at both supra- and near-threshold intensities.

190         Based on previous studies with self-initiated sounds of high and low intensities, we  
191 expected to observe i) sensory attenuation for self- compared to externally-generated  
192 sounds at supra-threshold intensities and ii) sensory enhancement for self- compared to  
193 externally-generated sounds at near-threshold intensities. This interaction would be evident  
194 by better detection performance for the self- as compared to the externally-generated  
195 sounds (lower detection thresholds as in Reznik et al., 2014). Similarly, in the  
196 discrimination task, this interaction would be reflected in i) lower point of subjective  
197 equality for self- compared to externally-generated sounds at supra-threshold intensities  
198 (cf., Reznik et al., 2015; Sato, 2008; Weiss et al., 2011a) and ii) higher point of subjective  
199 equality for self- compared to externally-generated sounds at near-threshold intensities  
200 (Reznik et al., 2015). Finally, based on previous studies reporting that self-generation only

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201 affects perceived loudness, rather than discrimination sensitivity (e.g., Sato, 2008; Weiss et  
202 al., 2011a, 2011b), we did not expect any significant differences in the just noticeable  
203 difference values, at least for the supra-threshold conditions.

204 The hypotheses and planned analyses for this study were preregistered on the Open  
205 Science Framework (<https://osf.io/ypajr/>). The Method and Results sections follow the  
206 preregistered plan.

## 207 **2. Methods**

208 Methods follow the preregistered plan (<https://osf.io/ypajr/>). The present study  
209 consisted of two two-alternative forced-choice (2AFC) tasks: a detection and a  
210 discrimination task. In the detection task, participants were presented with one sound at  
211 varying intensities and had to indicate whether it was presented in a first or a second  
212 interval of time, while in the discrimination task two sounds were presented in two different  
213 consecutive intervals of time and participants had to indicate whether the first sound  
214 (standard) or the second sound (comparison) was louder. The order of tasks was  
215 counterbalanced across participants.

### 216 *2.1. Participants*

217 Thirty-one healthy, normal-hearing subjects, participated in the present study.  
218 Participants were typically undergraduate university students at the University of  
219 Barcelona. Participants with hearing thresholds above 20 dB, psychiatric or neurological  
220 illness, aged below 18 or above 50 years old and who consumed drugs or pharmaceuticals  
221 acting on the central nervous system were excluded. Data from three participants (i.e.,  
222 participants 2, 19, 25) had to be excluded due to technical problems or inability to comply

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223 with the task instructions, leaving data from twenty-eight participants (6 men, 22 women,  
224  $M_{age} = 23$ , age range: 18–33 years). The sample size was defined based on the preregistered  
225 a priori power analysis. All participants gave written informed consent for their  
226 participation after the nature of the study was explained to them and they were monetarily  
227 compensated (10 euros per hour). Additional materials included a personal data  
228 questionnaire and a data protection document. The study was accepted by the Bioethics  
229 Committee of the University of Barcelona and all provisions of the Declaration of Helsinki  
230 were followed.

### 231 *2.2. Apparatus*

232 The visual stimuli were presented on an ATI Radeon HD 2400 monitor. The  
233 auditory stimuli were presented via the Sennheiser KD 380 PRO noise cancelling  
234 headphones. To record participants' button presses and behavioural responses, we used the  
235 Korg nanoPAD2. The buttons of this device do not produce any mechanical noise when  
236 pressed, and, thus, do not interfere with our auditory stimuli. The presentation of the stimuli  
237 and recording of participants' button presses and responses were controlled using  
238 MATLAB R2007a (The Mathworks Inc., 2017), and the Psychophysics Toolbox extension  
239 (Brainard, 1997; Kleiner et al., 2007; Pelli, 1997).

### 240 *2.3. Stimuli*

241 In the detection task we used pure tones presented binaurally with durations of 300  
242 ms at a frequency of 1000 Hz (created using MATLAB R2007a; The Mathworks Inc.,  
243 2017). The sampling frequency was 44100 Hz, the ramp duration (duration of the onset and  
244 offset ramps) was 25 ms and a number of 16 bits per sample (cf. Reznik et al., 2014, 2015).

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245 The tone intensity ranged from 0 dB to 28 dB in steps of 4 dB for passive and active  
246 conditions.

247 For the discrimination task, we created pure tones with the same characteristics as  
248 those used in the detection task, except for the intensities. The intensities for the standard  
249 and comparison tones were partly based on those used in previous studies (Reznik et al.,  
250 2015; Sato, 2008; Weiss et al., 2011a, 2011b). The standard tone was always presented at a  
251 fixed intensity, while the comparison intensities varied. Specifically, the standard tones had  
252 a fixed intensity of 74 dB for supra-threshold conditions, while for the near-threshold  
253 conditions we used a fixed intensity of 5 dB above the threshold as obtained from the  
254 audiometry for the 1000 Hz sounds (cf. Reznik et al., 2015). The comparison supra-  
255 threshold stimuli varied randomly between 71 and 77 dB in steps of 1 dB, thereby resulting  
256 in seven possible comparison intensities: 71, 72, 73, 74, 75, 76, 77 (cf. Sato, 2008; Weiss et  
257 al., 2011a, 2011b). For near-threshold conditions, the comparison intensities were presented  
258 at intensities starting from 3 dB below to 3 dB above the standard intensity in steps of 1 dB,  
259 so as to match the comparison intensities of the supra-threshold conditions.

#### 260 *2.4. Procedure*

261 Participants were seated in a soundproof chamber and auditory stimuli were  
262 presented to both ears via headphones. Visual stimuli were presented by a computer screen  
263 located in front of the participants. Prior to each task, hearing thresholds were assessed with  
264 a standard pure-tone audiometry. Additionally, practice blocks were used so that  
265 participants could familiarize themselves with each task, which also allowed us to obtain  
266 the stimulus-onset-asynchrony (SOA) between interval-cue presentation and button press in  
267 order to introduce the same visual-to-sound delay in the first passive trials.

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268 *2.4.1. Detection task*

269 Participants performed a 2-Alternative Forced Choice auditory detection task, where  
270 they had to report whether a sound of varying intensities was presented in interval one or  
271 two (Figure 1a). The sounds were either self-generated (active trials) or passively presented  
272 by the computer (passive trials).

273 Every trial started with a fixation cross with a duration of 500 ms followed by two  
274 consecutive intervals with a duration of 800 ms each. In the active trials, the sound  
275 presentation was contingent on participants' button press. That is, participants had to press  
276 a button with their right hand once the visual cues "PRESS 1" and "PRESS 2" appeared in  
277 order to generate a sound that was triggered by the button press in either the 1<sup>st</sup> or the 2<sup>nd</sup>  
278 interval. For the intervals containing the sound (either 1<sup>st</sup> or 2<sup>nd</sup>), the participants' button  
279 press triggered the sound only if he/she pressed the button up to 300 ms prior to the interval  
280 offset. This allowed us to control that the sound had always a 300-ms duration in case a  
281 participant delayed the button press. In the passive trials, participants were passively  
282 presented with a sound in one of the two intervals indicated by the visual cues "LISTEN 1"  
283 and "LISTEN 2". To match the timing of the sound in the active conditions, the sound was  
284 presented after an interval that was randomly selected from the participants' distribution of  
285 press times in the active trials performed until the current trial. Thus, the timing of the  
286 stimulus presentation was equal for the two types of trials, thereby minimizing any effects  
287 of temporal predictability on the ability to detect self- and externally-generated sounds  
288 (Horvath, 2015; Hughes et al., 2013). After the offset of the second interval, the question  
289 "Did you hear the sound in the 1<sup>st</sup> or 2<sup>nd</sup> interval?" appeared on the screen for 1500 ms and  
290 participants had to press a button with their left hand within this time window to respond.

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291 For both trials, once a response was provided the question displayed on the screen  
292 disappeared immediately. The next trial started always after the 1500 ms response window  
293 was over.

294 The whole task was divided into 25 blocks consisting of 40 trials, resulting in 1000  
295 trials in total (500 active and 500 passive trials). Active and passive conditions were  
296 presented randomly intermixed within each block (20 active and 20 passive trials). The  
297 intensities were presented using the method of constant stimuli. Intensities from 0 dB to 24  
298 dB were presented a total of 70 times each for each condition, while we only presented the  
299 sound at 28 dB 10 times for each condition to save experimental time, given that pilot data  
300 showed ceiling performance at this intensity level. The interval containing the sound  
301 (interval 1 or 2) was random.

#### 302 *2.4.2. Discrimination task*

303 In the discrimination task two sounds were presented in two different consecutive  
304 intervals and participants had to indicate whether the first (standard) or the second sound  
305 (comparison) was louder (Figure 1b). Similarly to the detection task, there were two types  
306 of trials, passive and active. However, there were two additional intensity conditions, supra-  
307 and near-threshold, thereby resulting in 4 possible types of trials in total: Active and Supra-  
308 threshold (AS), Passive and Supra-threshold (PS), Active and Near-threshold (AN) and  
309 Passive and Near-threshold (PN).

310 Each trial started with a fixation cross with a duration of 500 ms followed by two  
311 consecutive intervals with a duration of 800 ms each. In the active trials, participants had to  
312 press a button with their right hand in the first interval, instructed by the cue “PRESS:

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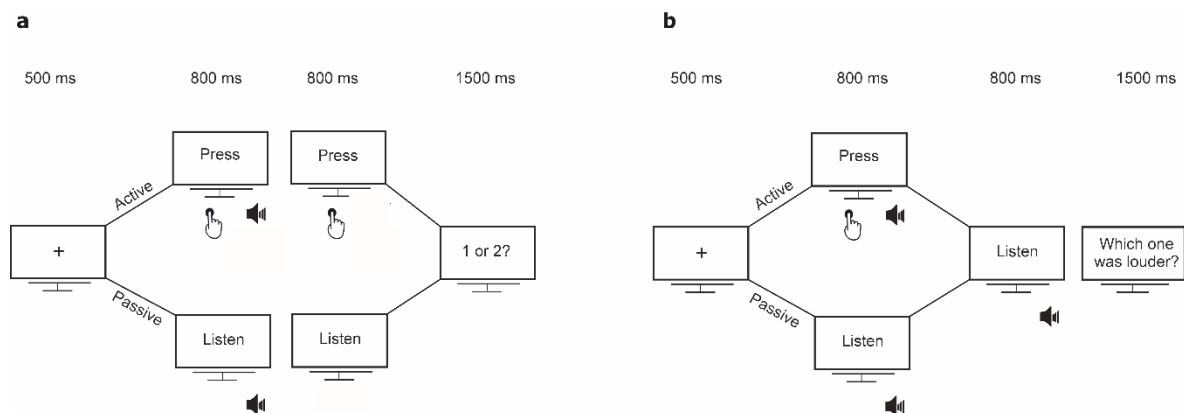
313 sound 1”, in order to generate the standard tone. The comparison sound was passively  
314 presented in the second interval of time following the visual cue “LISTEN: sound 2”. The  
315 interval between visual cue and comparison sound onset was randomly selected from the  
316 participants’ distribution of press times in the first interval. For the standard self-generated  
317 sound, the participants’ button press triggered the sound only if he/she pressed the button  
318 up to 300 ms prior to the interval offset. This allowed us to control that the sound had  
319 always a 300-ms duration in case a participant delayed the button press. In the passive  
320 trials, participants were passively presented with two sounds in the 1<sup>st</sup> and the 2<sup>nd</sup> interval,  
321 respectively, indicated by the visual cues “LISTEN: sound 1” and “LISTEN: sound 2”. The  
322 sounds were presented after an interval that was randomly selected from the participants’  
323 distribution of press times in the active trials. Unbeknownst to the subjects, the standard  
324 tone was always presented at the same intensity within each intensity condition: 74 dB for  
325 supra-threshold conditions and 5 dB above the threshold obtained from the audiometry for  
326 near-threshold conditions. In contrast, the comparison sound ranged from 71 dB to 77 dB in  
327 steps of 1 dB for supra-threshold conditions and  $\pm 3$  dB in steps of 1 dB relative to the  
328 standard tone for near-threshold conditions. After the offset of the second comparison  
329 interval, the question “Which sound was louder: Sound 1 or Sound 2?” appeared on the  
330 screen for 1500 ms and participants had to press a button with their left hand to indicate  
331 whether the first (left button) or the second (right button) sound was louder. To control for  
332 the possibility that participants did not hear the near-threshold sounds, a third control  
333 button was used, and participants were instructed to press it only if they did not hear the  
334 two sounds. After participants’ response, the question disappeared immediately. The next  
335 trial started always after the 1500 ms response window was over.



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336 The task was divided in 25 blocks, each one consisting of 28 trials. Each of the  
337 seven possible comparison tone intensities was presented 25 times per condition using the  
338 method of constant stimuli, as it yields a better estimation of the Point of Subjective  
339 Equality (PSE) and Just Noticeable Difference (JND) values compared to other methods  
340 (Guilford, 1954). This resulted in 175 trials per experimental condition (active/passive and  
341 supra-/near-threshold) and 700 trials in total for each participant. The conditions (i.e.,  
342 sound-source: active vs. passive, and intensity: supra- vs. near-threshold) were intermixed  
343 within each block and the order of presentation was randomized for each participant.

344



345 **Figure 1.** Schematic illustration of the experimental design. a) *Detection task*: Each trial  
346 started with a fixation cross, followed by two intervals. In active trials, participants were  
347 instructed to press a button in each interval (“Press” cue) and a sound was triggered either  
348 in 1<sup>st</sup> or in the 2<sup>nd</sup> one (in the example shown here, the sound is presented in the 1<sup>st</sup>  
349 interval). In passive trials, the sound was passively presented (“Listen” cue). Participants  
350 had to respond whether they heard the sound in the 1<sup>st</sup> or in the 2<sup>nd</sup> interval. b)  
351 *Discrimination task*: Each trial started with a fixation cross, followed by two sounds. The  
352 first sound was either self- (active trials; “Press” cue) or externally-generated (passive  
353 trials; “Listen” cue) and was presented at an intensity of either 74 dB (suprathreshold  
354 intensity) or 5 dBs above each participant’s audiometric threshold (near-threshold  
355 intensity). The second sound was always externally-generated (“Listen” cue) and ranged  
356  $\pm 3$  dB in steps of 1 dB relative to the first one. Participants had to respond which one was  
357 louder.  
358

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359 *2.5. Modifications from the preregistered plan*

360 This experiment was preregistered on the Open Science Framework (<https://osf.io/ypajr/>).  
361 Relative to our preregistered plan, we made one modification: Instead of fitting the  
362 psychometric function with the Palamedes Toolbox (Kingdom & Prins, 2016) as reported  
363 in the preregistration of this study, we decided to use the quickpsy package in R (Linares &  
364 López-Moliner, 2016) for better visualization of the data and in order to directly introduce  
365 the values obtained from the fitting procedure to statistical analysis in R. The change in the  
366 toolbox used is not expected to have affected the results, as we kept all the parameters as  
367 predefined in the preregistration.

368 *2.6. Data analysis*

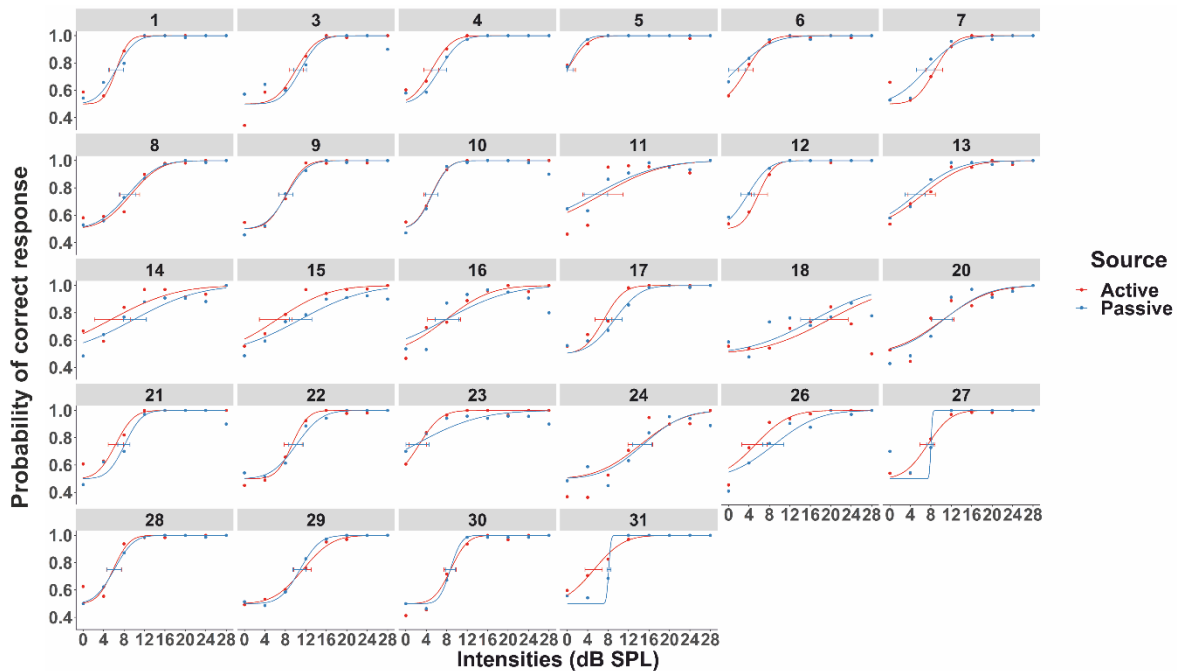
369 Data analysis follows the preregistered plan. All analysis code will be publicly  
370 released with the data upon publication (<https://osf.io/ypajr/>).

371 *2.6.1. Detection task*

372 For each participant, the percentage of correct answers were calculated for each  
373 intensity and condition – active and passive –. Subsequently, for each condition, the  
374 percentage of correct responses was fitted with a normal cumulative function (Figure 2)  
375 according to the maximum likelihood procedure, using the quickpsy package in R (Linares  
376 & López-Moliner, 2016). For each participant and condition, two parameters were  
377 extracted from the model: alpha (i.e., values for thresholds in the range of the intensity  
378 levels we used) and beta (i.e., values for slope in the range of 0 to 10 in steps of .1). The  
379 lower asymptote of the psychometric function (i.e., gamma) was set to 0.5 as in previous 2-  
380 AFC detection tasks, while the upper asymptote (i.e., lambda), which corresponds to the

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381 lapse rate, was set to .001 (Kingdom & Prins, 2016). For each participant and condition,  
382 goodness-of-fit and the 95% confidence intervals for thresholds were calculated by a  
383 parametric bootstrap procedure ( $n = 1000$ ; Efron & Tibshirani, 1994), using the quickpsy  
384 package in R (Linares & López-Moliner, 2016).



386 **Figure 2.** Psychometric functions for 28 participants from the detection task fitted to the  
387 percent correct responses as a function of sound intensity. Number in the legend above each  
388 plot corresponds to each participant's number (participants with numbers 2, 19, 25 were  
389 excluded; see Methods). The small horizontal segments represent the 95% confidence  
390 intervals for thresholds (parametric bootstrap procedure with  $n = 1000$ ). The threshold is  
391 defined as the intensity accurately detected at 75% of the trials (as derived from the  
392 psychometric function fitted for each participant) and is represented by the intersection of  
393 the confidence interval with the psychometric function.

394

395 The second part of the analysis consisted in calculating the  $d'$  sensitivity index and  
396 criterion in order to directly compare our results with previous studies using this measure  
397 (Reznik et al., 2014). This analysis was performed using the Palamedes toolbox (version  
398 1.10.3; Kingdom & Prins, 2016). Given that here we employed a 2-AFC task, we first

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399 calculated the hit and false alarm rate for one of the two intervals (interval 1 as target). As  
400 hit for interval 1 were defined the trials, where the sound was in interval 1 and the  
401 participant responded that the sound was indeed presented in this interval. As false alarm  
402 for interval 1 were defined the trials, where the participant incorrectly detected the sound in  
403 interval 1, while the stimulus was actually presented in interval 2. Subsequently, we  
404 calculated the hit rate (= number of hits divided by the number of signal trials, i.e., trials  
405 where the sound was presented in the 1<sup>st</sup> interval) and the false alarm rate (= number of  
406 false alarms divided by the number of noise trials, i.e., trials where the sound was presented  
407 in the 2<sup>nd</sup> interval). After z-transforming the hit and false alarm rates, we calculated the d'  
408 (i.e.,  $z(\text{Hit}) - z(\text{False Alarm})$ ) and criterion (i.e.,  $-0.5 * z(\text{Hit}) - z(\text{False Alarm})$ ) for active  
409 and passive trials. Finally, we calculated the mean interval between the cue presentation  
410 and participants' button press (henceforth SOAs) in the active trials.

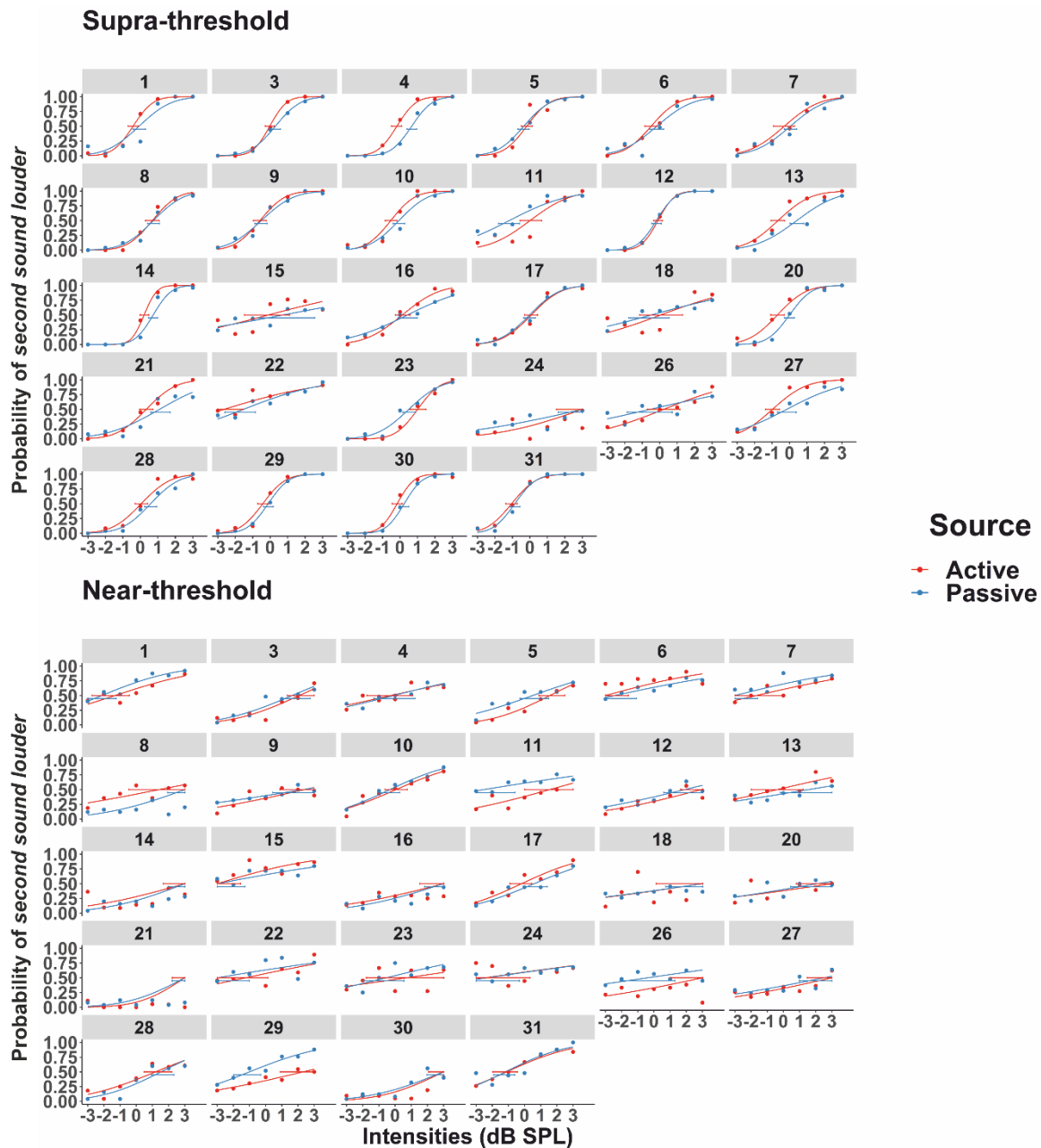
#### 411 2.6.2. Discrimination task

412 For each participant, the proportion of “second sound louder” responses was  
413 calculated for each condition (active/passive, supra-/near-threshold) and for the seven  
414 comparison intensities. Data from the trials where participants did not hear the near-  
415 threshold sounds (as indicated by the third control button; see Procedure) were excluded  
416 from the analysis. In order to directly compare performance across supra- and near-  
417 threshold conditions, we defined the comparison intensities as the difference in dB from the  
418 standard stimulus: -3, -2, -1, 0, 1, 2, 3. The “second sound louder” responses for each  
419 condition were, then, fitted with a normal cumulative function (Figure 3) according to the  
420 maximum likelihood procedure, using the quickpsy package in R (Linares & López-  
421 Moliner, 2016). For each participant and condition, two parameters were extracted from the

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422 model: alpha (i.e., values in the range of the comparison intensity levels we used) and beta  
423 (i.e., values for slope in the range of 0 to 10 in steps of .1). The lower asymptote of the  
424 psychometric function (i.e., gamma) was set to 0 as in previous 2-AFC discrimination  
425 tasks, while the upper asymptote (i.e., lambda), which corresponds to the lapse rate, was set  
426 to .001 (Kingdom & Prins, 2016). Thus, for each participant and condition, two measures  
427 were obtained. First, the Point of Subjective Equality (PSE), which corresponds to the  
428 alpha values of the model, and is defined as the intensity, where the comparison stimulus  
429 was reported as louder than the standard one on 50% of the trials. This value is used to  
430 estimate the comparison tone intensity that would make the standard and comparison tones  
431 perceptually equal and is considered an index of perceptual bias (Bausenhardt, Di Luca, &  
432 Ulrich, 2018). Higher PSE values would indicate that the standard first tone is perceived as  
433 louder, while lower PSE values would reflect an attenuated perceived loudness for this  
434 sound. Thus, shifts of the PSE values from the Point of Objective Equality (i.e., the point  
435 indexing the physical equality of the two sounds, which is 0 dBs here) would reflect a  
436 biased estimate of perceived loudness. Second, we extracted the just noticeable difference  
437 (JND), which corresponds to the beta values of the model (i.e., the standard deviation  
438 extrapolated from the fit) and is considered a measure of precision associated with the  
439 estimate. Higher JND values would reflect lower precision in discriminating the loudness  
440 of the two sounds (i.e., lower differential sensitivity; Gescheider, 1997). For each  
441 participant and condition, goodness-of-fit and the 95% confidence intervals for PSE were  
442 calculated by a parametric bootstrap procedure ( $n = 1000$ ; Efron & Tibshirani, 1994), using  
443 the quickpsy package in R (Linares & López-Moliner, 2016). Finally, we calculated the  
444 mean interval between the cue presentation and participants' button press (henceforth  
445 SOAs) in the active trials.

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448 **Figure 3.** Psychometric functions for 28 participants from the discrimination task fitted to  
 449 the probability of judging the comparison sound as louder as a function of its difference in  
 450 dB from the first standard tone ( $\pm 3$  dB in steps of 1) for the supra- and the near-threshold  
 451 intensities, respectively. Number in the legend above each plot corresponds to each  
 452 participant's number (participants with numbers 2, 19, 25 were excluded; see Methods).  
 453 The small horizontal segments represent the 95% confidence intervals (parametric  
 454 bootstrap procedure with  $n = 1000$ ) for the point of subjective equality (PSE), which is  
 455 defined as the intensity, where the comparison stimulus was reported as louder than the  
 456 standard one on 50% of the trials.

### 457 **3. Results**

458 All statistical analyses were performed using R (version 3.6.0). For all the  
459 significant results in the ANOVA, we report the eta generalized squared effect size ( $\eta_G^2$ )  
460 and the eta partial squared ( $\eta_p^2$ ), since the  $\eta_G^2$  is less biased than  $\eta_p^2$  (Bakeman, 2005;  
461 Olejnik, & Algina, 2003), but we also wanted to compare our findings with other studies  
462 that usually report the  $\eta_p^2$  effect size.

#### 463 *3.1. Modifications from the preregistered plan*

464 This experiment was preregistered on the Open Science Framework  
465 (<https://osf.io/ypajr/>). Relative to our preregistered analyses, we made one modification:  
466 For the detection task, we initially planned to perform a paired-samples t-test to test for  
467 differences in the slope of the psychometric function. However, considering that the  
468 normality test was violated (Shapiro-Wilk normality test,  $p < .05$ ), we performed a non-  
469 parametric Wilcoxon test.

#### 470 *3.2. Audiometry*

471 From each audiometry, we obtained the thresholds for both the left and right ear.  
472 For all subjects, the thresholds were below 20 dB. Considering that in both tasks, we  
473 utilized a pure tone of 1000 Hz, in this analysis we only considered the thresholds for the  
474 1000-Hz sounds. Specifically, for each audiometry we calculated the means across the two  
475 ears. The mean thresholds were subsequently introduced in a statistical analysis using a  
476 paired-sampled two-sided t-test to test for differences in audiometric thresholds prior to  
477 each task. The analysis did not show any significant differences ( $M_{AM\_Detection} = 12.26$ ,

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478  $M_{AM\_Discrimination} = 11.22$ ,  $SD_{AM\_Detection} = 3.74$ ,  $SD_{AM\_Discrimination} = 3.81$ ,  $p > .05$ ; Shapiro-Wilk  
479 normality test,  $p > .05$ ).

### 480 3.3. Detection Task

481 The thresholds, slopes,  $d'$ , and criterion values, were analyzed using paired samples  
482 t-tests with the factor sound source – active (A) or passive (P). Trials with erroneous  
483 presses (i.e., late onset time of button press and no presses) were excluded from all analyses  
484 ( $M_A = 28.26\%$ ,  $SD_A = 20.37$   $M_P = 2.35\%$ ,  $SD_P = 3.3$ ). For the active trials, the mean  
485 interval between cue onset and button press was 0.39 s ( $SD = .07$ ) for Interval 1 and 0.16 s  
486 ( $SD = .14$ ) for Interval 2.

487 First, we performed statistical analyses for the measures obtained from the  
488 psychometric fitting procedure (Figure 4). To test for differences between the thresholds in  
489 the active and passive conditions, we used a paired samples one-tailed t-test with the  
490 hypothesis of expecting lower detection thresholds (i.e., better detection ability) in the  
491 active compared to passive trials (cf. Reznik et al., 2014; Shapiro-Wilk normality test  $p >$   
492  $.05$ ). The analysis did not show any significant differences between the active and the  
493 passive conditions ( $t(27) = -1.09$ ,  $p > .05$ ,  $M_A = 7.46$ ,  $M_P = 7.85$ ,  $SD_A = 3.7$ ,  $SD_P = 3.66$ ),  
494 suggesting that self-generation does not have any effect on participants' detection  
495 thresholds. Subsequently, we tested for possible differences in the slope of the  
496 psychometric function. Considering that the assumption of normality was violated  
497 (Shapiro-Wilk normality test  $p = .02$ ), we performed a nonparametric Wilcoxon's signed  
498 rank test for paired data on the beta values obtained from the fitting of the psychometric  
499 functions. The analysis did not show any significant difference between the active and  
500 passive slopes ( $W = 146$ ,  $p > .05$ ,  $M_A = 4.65$ ,  $M_P = 5.05$ ,  $SD_A = 2.48$ ,  $SD_P = 3.11$ ).



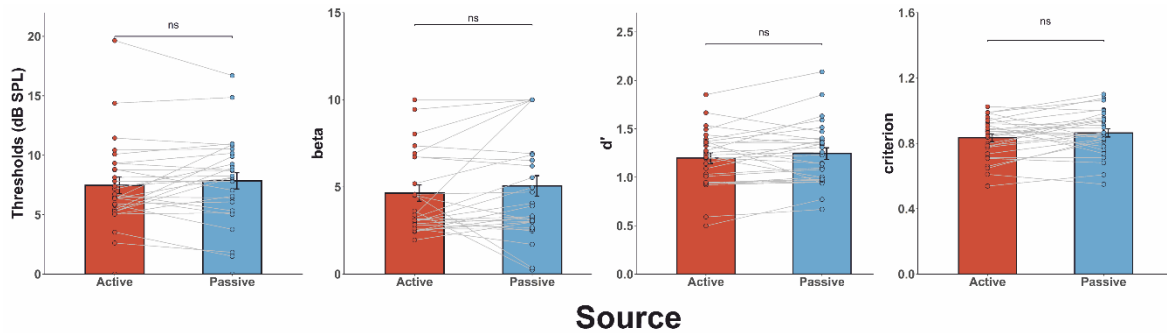
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501 To analyze the differences in the thresholds between the two conditions, we also  
502 calculated a 95% confidence interval for the difference in thresholds based on the  
503 simulations from the bootstrapping procedure ( $n = 1000$ ). For 23 out of the 28 subjects no  
504 significant differences were observed between the active and the passive trials. For one of  
505 them, the comparison between observed and simulated thresholds showed a significantly  
506 higher threshold for the active compared to the passive trials, while for the other four, a  
507 significantly lower threshold was obtained for the active trials. The goodness-of-fit routine  
508 showed that for the active trials, 26 out of the 28 psychometric curves resulted in acceptable  
509 goodness-of-fit statistics, while the fitting procedure for the passive trials showed  
510 acceptable goodness-of-fit statistics for 25 out of the 28 psychometric curves.

511 Subsequently, we performed a signal detection analysis for the  $d'$  and criterion  
512 values, after confirming that the normality assumption was not violated (Figure 4; Shapiro-  
513 Wilk normality test,  $p > .05$ ). The  $d'$  values were analyzed using a paired samples one-  
514 tailed t-test with the hypothesis of expecting higher  $d'$  in active compared to passive trials  
515 (cf. Reznik et al., 2014). Contrary to previous work (Reznik et al., 2014), the analysis did  
516 not show any significant differences between the active vs. passive  $d'$  values ( $M_A = 1.2$ ,  
517  $SD_A = 0.3$ ,  $M_P = 1.24$ ,  $SD_P = .32$ ,  $p > .05$ ). Similarly, the criterion values were analyzed  
518 using a paired-samples two-tailed t-test (cf. Reznik et al., 2014). Similar to the findings  
519 obtained by Reznik et al. (2014), we did not observe any significant difference in the  
520 criterion values between active and passive trials ( $M_A = .83$ ,  $SD_A = .12$ ,  $M_P = .86$ ,  $SD_P =$   
521  $.13$ ,  $p > .05$ ). Collectively, these findings suggest that self-generation does not affect  
522 detection sensitivity nor response bias in a 2-AFC detection task.

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**Figure 4.** Summary of the results from the detection task. Mean ( $\pm$ s.e.m.) threshold, beta value for slope,  $d'$  score, and criterion. There were no significant differences between active and passive in the threshold (one-tailed paired samples t-test,  $p > .05$ ), slope (i.e., beta values from the psychometric fitting procedure; nonparametric Wilcoxon test due to violation of normality assumption,  $p > .05$ ),  $d'$  score (one-tailed paired samples t-test,  $p > .05$ ), or criterion (two-tailed paired samples t-test,  $p > .05$ ).

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To further test for possible effects of self-generation and intensity level on detection performance, we also analyzed the percent of correct responses for both the active and passive trials for each one of the intensity levels. These analyses were performed so as to examine whether detection accuracy for self-generated sounds varied across the intensity levels used. We, first, conducted a repeated measures ANOVA with factors Intensity (0, 4, 8, 12, 16, 20, 24, 28) and Source (active and passive) on accuracy. The Greenhouse-Geisser correction was applied where sphericity was violated. The analysis did not show any significant main effect of source ( $F(1,27) = 1.64, p > .05$ ), but we obtained a significant main effect of intensity,  $F(2.35,63.44) = 228.79, p < .001, \eta_p^2 = .89$  and  $\eta_G^2 = .78$ . Specifically, irrespective of whether the sound was self- or externally-generated, participants' accuracy was significantly lower at 0 dBs compared to the rest of the intensities, at 4 dBs compared to the intensities above 8 dBs, at 8 dBs compared to the intensities above 12 dBs, and at 12 dBs compared to intensities above 16 dBs (all  $p < .001$ ;  $M_0 = 54.65, SD_0 = 8.85, M_4 = 61.19, SD_4 = 11.9, M_8 = 77.99, SD_8 = 13.33, M_{12} = 92.53,$

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546  $SD_{12} = 8.88$ ,  $M_{16} = 96.47$ ,  $SD_{16} = 6.03$ ,  $M_{20} = 97.4$ ,  $SD_{20} = 4.36$ ,  $M_{24} = 97.37$ ,  $SD_{24} = 4.79$ ,  
547  $M_{28} = 97.26$ ,  $SD_{28} = 8.09$ ). Comparisons between higher intensities (i.e., 16 – 28 dBs) did  
548 not show any significant differences in participants' accuracy. The interaction between  
549 source and intensity did not reach significance ( $F(4,10,110.68) = .62$ ,  $p > .05$ ).

### 550 3.4. Discrimination Task

551 The PSE and JND values were analyzed using a repeated measures analysis of  
552 variance (ANOVA) with two factors: sound source – active (A) or passive (P) – and sound  
553 intensity – supra- (S) or near-threshold (N) intensity –. Trials with erroneous presses (i.e.,  
554 late onset time of button press and no presses) were excluded from all analyses ( $M = 12.16$   
555 %,  $SD = 10.24$ ). For the active trials, the mean interval between cue onset and button press  
556 was 0.37 s ( $SD = .06$ ).

557 The analysis for the PSE values revealed that there was not a main effect of source  
558 ( $F(1,27) = .8$ ,  $p > .05$ ;  $M_A = .39$ ,  $M_P = .25$ ,  $SD_A = 1.65$ ,  $SD_P = 1.65$ ) nor a main effect of  
559 intensity ( $F(1,27) = 2.62$ ,  $p > .05$ ;  $M_N = .65$ ;  $M_S = -.008$ ,  $SD_N = 2.12$ ,  $SD_S = .86$ ). However,  
560 there was a significant interaction between source and intensity ( $F(1,27) = 12.10$ ,  $p = .002$ ,  
561  $\eta_p^2 = .31$  and  $\eta_G^2 = .15$ ; Figure 5). The Bonferroni corrected post-hoc tests revealed a  
562 significantly higher PSE for the AN condition compared with the AS condition ( $M_{AN} = .92$ ,  
563  $M_{AS} = -.13$ ,  $SD_{AN} = 2.04$ ,  $SD_{AS} = .9$ ,  $t(27) = -2.48$ ,  $p = .02$ ,  $d = .47$ ; two-tailed post-hoc t-  
564 test), a significantly lower PSE for the AS compared to the PS condition ( $M_{AS} = -.13$ ,  $M_{PS}$   
565  $= .12$ ,  $SD_{AS} = .9$ ,  $SD_{PS} = .83$ ,  $t(27) = -2.41$ ,  $p = .02$ ,  $d = .45$ ; one-tailed post-hoc t-test), and  
566 a significantly higher PSE for the AN compared to the PN condition ( $M_{AN} = .92$ ,  $M_{PN} = .39$ ,  
567  $SD_{AN} = 2.04$ ,  $SD_{PN} = 2.19$ ,  $t(27) = 2.09$ ,  $p = .02$ ,  $d = .39$ ; one-tailed post-hoc t-test). The  
568 post-hoc analysis did not show significant differences between the PS and the PN condition

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569 ( $M_{PS} = .12$ ,  $M_{PN} = .39$ ,  $SD_{PS} = .83$ ,  $SD_{PN} = 2.19$ ,  $t(27) = -.64$ ,  $p > .05$ ; two-tailed post-hoc t-  
570 test). Thus, we replicate the findings obtained by previous discrimination studies with  
571 supra-threshold sounds (e.g., Sato, 2008; Weiss et al., 2011a, 2011b), by showing that self-  
572 generated supra-threshold sounds are attenuated compared to identical, yet externally  
573 presented stimuli. More importantly, though, we extend previous work, by showing that  
574 self-generation yields the opposite effect on perceptual bias when stimuli are presented at  
575 near-threshold intensities. That is, self-generated near-threshold sounds are perceived  
576 louder compared to the passively presented ones.

577         The analysis for the JND values revealed that there was a significant main effect of  
578 intensity ( $F(1,27) = 119.45$ ,  $p < .001$ ,  $\eta_p^2 = .82$  and  $\eta_G^2 = .49$ ), with a significantly higher  
579 JND for the supra- compared to the near-threshold conditions ( $M_S = 1.93$ ,  $M_N = 5.79$ ,  $SD_S =$   
580  $1.5$ ,  $SD_N = 2.39$ ), thus pointing to lower discrimination sensitivity for near- compared to  
581 supra-threshold sounds (Figure 5). The analysis did not show a significant main effect of  
582 source ( $F(1,27) = 2.75$ ,  $p > .05$ ;  $M_A = 3.68$ ,  $M_P = 4.03$ ,  $SD_A = 2.7$ ,  $SD_P = 2.9$ ) nor a  
583 significant interaction between source and intensity ( $F(1,27) = .77$ ,  $p > .05$ ). Collectively,  
584 the results obtained by these analyses are consistent with previous work with both auditory  
585 (e.g., Sato, 2008; Weiss et al., 2011a, 2011b) and tactile self-generated stimuli (e.g., Kilteni  
586 et al., 2020) and further show that rather than being dependent on participants' differential  
587 sensitivity in discriminating the loudness of two sounds (as indexed by the JND values), the  
588 interactive effects of intensity and self-generation are mainly driven by biases in the  
589 loudness estimates (as indexed by the PSE values).

590         For analyzing differences in the PSE between the four conditions, the 95%  
591 confidence intervals were calculated for each condition based on the simulations from the

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592 bootstrapping procedure (n = 1000). For 9 subjects we found significant differences  
593 between the active and passive supra-threshold conditions (for 8 subjects, lower PSE in the  
594 AS compared to the PS), while for the near-threshold intensities only 3 subjects had  
595 significantly higher PSE values in the active compared to the passive condition. Within the  
596 active condition, significant differences were obtained between the supra- and near-  
597 threshold intensities for 16 subjects (for 13 subjects, lower PSE in the AS compared to the  
598 AN), while for 18 subjects we found significant differences between the passive supra- and  
599 passive near-threshold conditions (for 12 subjects, lower PSE in PS compared to PN). The  
600 goodness-of-fit routine showed that for 26, 27, 26, and 26 psychometric curves out of the  
601 28 total curves fitted per condition, the fitting procedure resulted in acceptable goodness of-  
602 fit statistics (for the AN, AS, PN, and PS, respectively).

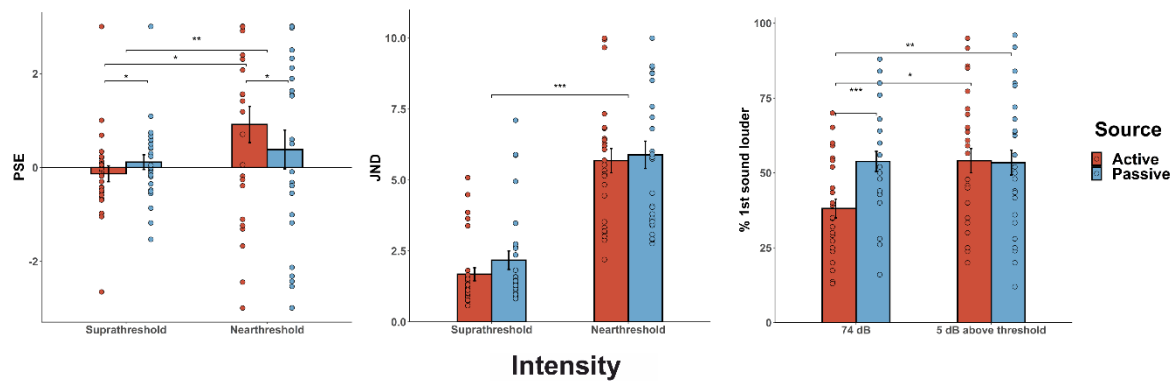
603         Finally, we aimed to directly compare our results with the findings obtained by  
604 Reznik et al. (2015), where they employed a similar discrimination task where the standard  
605 and comparison tone were always presented at the same intensity (either supra- or near-  
606 threshold). To this end, in this analysis we only included the trials where the comparison  
607 sound was presented at the same intensity as the standard one. In particular, for the supra-  
608 threshold condition we only included the trials where the comparison sounds was presented  
609 at 74 dB (i.e., same intensity as the standard supra-threshold sounds), and accordingly for  
610 the near-threshold condition we only considered trials where the comparison tone was  
611 presented 5 dBs above each participant's audiometric threshold (i.e., as the standard near-  
612 threshold sounds). In order to directly compare with Reznik et al.'s study, we calculated the  
613 "1<sup>st</sup> sound louder" instead of "2<sup>nd</sup> sound louder" responses and performed a 2x2 repeated  
614 measures ANOVA with the factors sound source (active or passive) and sound intensity

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615 (supra- or near-threshold). The results showed a significant main effect of source ( $F(1,27) =$   
616  $13.54, p < .001, \eta_p^2 = .33$  and  $\eta_G^2 = .04$ ), with less “1<sup>st</sup> sound louder” responses for active  
617 compared to passive trials ( $M_A = 46.1, SD_A = 20.62, M_P = 53.63, SD_P = 19.86$ ). Contrary to  
618 the results reported in Reznik et al.’s study, the main effect of intensity did not reach  
619 significance ( $F(1,27) = 3.26, p > .05, M_N = 53.77, SD_N = 21.57, M_S = 45.98, SD_S = 18.76$ ).  
620 However, consistent with Reznik et al. (2015), we obtained a significant interaction  
621 between source and intensity ( $F(1,27) = 8.94, p < .01, \eta_p^2 = .25$  and  $\eta_G^2 = .04$ ; Figure 5).  
622 The post-hoc t-tests showed that while there were significantly less “1<sup>st</sup> sound louder”  
623 responses for AS compared to PS trials ( $M_{AS} = 38.12, M_{PS} = 53.82, SD_{AS} = 16.56, SD_{PS} =$   
624  $17.75, t(27) = -5.19, p < .001, d = .98$ ; one-tailed paired samples t-test), no differences were  
625 observed between active and passive trials when the sounds were presented at near-  
626 threshold intensities ( $M_{AN} = 54.09, M_{PN} = 53.45, SD_{AN} = 21.43, SD_{PN} = 22.10, t(27) = .17, p$   
627  $= .57$ ; one-tailed paired samples t-test). Interestingly, consistent with the results obtained  
628 for the PSE, we also observed significantly more “1<sup>st</sup> sound louder responses” for the AN  
629 compared to the AS condition ( $M_{AN} = 54.09, SD_{AN} = 21.43, M_{AS} = 38.12, SD_{AS} = 16.56,$   
630  $t(27) = -3.03, p = .01, d = .01$ ; two-tailed paired samples t-test), while no differences were  
631 obtained between the PS and PN conditions ( $M_{PS} = 53.82, SD_{PS} = 17.75, M_{PN} = 53.45, SD_{PN}$   
632  $= 22.10, t(27) = .08, p = .84$ ; two-tailed paired samples t-test). Collectively, the comparison  
633 analysis we performed replicates the significant interaction reported by Reznik et al. (2015)  
634 with an even larger effect size ( $\eta_p^2 = .25$  here compared to  $\eta_p^2 = .21$  in Reznik et al.), but the  
635 follow-up analyses demonstrate that when the standard and comparison tones are presented  
636 at the same intensity, the differences between self- and externally-generated sounds are  
637 limited to supra-threshold intensities.

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640 **Figure 5.** Summary of the results from the discrimination task. Mean ( $\pm$ s.e.m.) PSE, JND,  
641 and percent of “1<sup>st</sup> sound louder responses” (cf. Reznik et al., 2015). From left to right:  
642 Significant interaction between source and intensity on PSE ( $p < .01$ ), with the post-hoc  
643 comparisons showing lower PSE for the active supra-threshold compared to the passive  
644 supra-threshold condition (one-tailed paired samples post-hoc t-test;  $p < .05$ ), significantly  
645 higher PSE for the active near-threshold compared to the passive near-threshold condition  
646 (one-tailed paired samples post-hoc t-test;  $p < .05$ ), and significantly higher PSE for the  
647 active near-threshold compared to active supra-threshold (two-tailed paired samples post-  
648 hoc t-test;  $p < .05$ ). Significant main effect of intensity on JND, with higher JND for the  
649 supra- compared to the near-threshold condition ( $p < .001$ ). For the “1<sup>st</sup> sound louder  
650 responses”, we only included trials where the standard and the comparison sounds were  
651 presented at the same intensity (i.e., 74 dB as a supra-threshold intensity and 5 dB above  
652 each participant’s threshold as a near-threshold intensity; cf. Reznik et al., 2015). There  
653 was a significant interaction between source and intensity ( $p < .01$ ), with the post-hoc  
654 comparisons showing less “1<sup>st</sup> sound louder” responses for active compared to passive  
655 trials when the sound was presented at 74 dB (one-tailed paired samples post-hoc t-test;  $p <$   
656  $.001$ ), less “1<sup>st</sup> sound louder” responses for active trials when presented at 74 dB compared  
657 to when presented at 5 dB above each participant’s threshold ( $p < .05$ ), and no differences  
658 between active and passive trials when the sounds were presented at 5 dB above each  
659 participant’s threshold (one-tailed paired samples post-hoc t-test;  $p > .05$ ).

660

### 661 3.5. Correlations

662 In an attempt to further test for possible links between detection and discrimination  
663 performance for both self- and externally-generated sounds, we conducted further  
664 correlation analyses with the values obtained from each task. Specifically, for both the self-  
665 and externally-generated sounds, we performed separate Pearson correlation analyses to



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666 assess the relationship between the detection thresholds and the PSE and JND values. For  
667 both self- and externally-generated sounds, no significant correlations were found between  
668 the detection thresholds and the PSE values (all  $p > .05$ ). However, for self-generated  
669 sounds, we obtained significant positive correlations between the detection thresholds and  
670 the JND values for both supra- and near-threshold conditions in the discrimination task  
671 (i.e.,  $r = 0.4$ ,  $p = .04$ ,  $CI = [.03 .67]$  and  $r = .48$ ,  $p = .01$ ,  $CI = [0.13 0.72]$ , respectively), thus  
672 pointing to a relation between detection and discrimination sensitivity. For externally-  
673 generated sounds, we obtained significant positive correlations between the detection  
674 thresholds and the JND values, but only for the sounds presented at supra-threshold  
675 intensities ( $r = .49$ ,  $p = .01$ ,  $CI = [.15 .73]$ ). Collectively, these analyses suggest that for  
676 self-generated sounds, increased detection thresholds correlate with lower discrimination  
677 precision (i.e., higher JND) for the same sounds presented both at supra- and near-threshold  
678 intensities, while increased detection thresholds for externally-generated sounds are only  
679 related with the discrimination sensitivity of the same sounds presented at supra-threshold  
680 intensities.

681       Additionally, we performed similar correlation analyses to test for possible links  
682 between the slope of the psychometric functions in the detection task and the PSE and JND  
683 values obtained from the discrimination task. As in the previous analysis, we did not  
684 observe any significant correlations between the slopes and the PSE values, neither for the  
685 self- nor for the externally-generated sounds. However, significant correlations were  
686 obtained again between the slopes and the JND values. For the self-generated sounds, we  
687 found significant positive correlations of the slope from the detection task with both the  
688 supra- and near-threshold conditions ( $r = .38$ ,  $p = .05$ ,  $CI = [.002 .66]$  and  $r = .4$ ,  $p = .04$ ,  $CI$



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689 = [.1 .71]). Similarly, for the externally-generated sounds, the slopes in the detection task  
690 correlated significantly with the JND values of both the supra- and near-threshold  
691 intensities ( $r = .46$ ,  $p = .01$ ,  $CI = [.11 .71]$  for both of them).

#### 692 **4. Discussion**

693 To-date, many different models have attempted to elucidate the effects of motor acts  
694 on perceptual processing. Yet, empirical evidence as to the exact direction and nature of  
695 these effects remain mixed. We hypothesized that the mixed findings may be related to the  
696 modulatory effects of stimulus intensity and to differences regarding the exact aspect of  
697 perceptual processing that is being tested (detection or discrimination ability; sensitivity or  
698 bias measures). Here, we present a preregistered study with a priori power estimations  
699 (<https://osf.io/ypajr/>), where we utilized a wide range of intensities to test for possible  
700 differences between self- and externally-generated sounds in detection and discrimination  
701 ability. Contrary to previous work (e.g., Reznik et al., 2014), we did not observe  
702 enhancements in the detection sensitivity for near-threshold self-generated sounds.  
703 However, in the discrimination task we found a significant interaction between self-  
704 generation and intensity on perceptual bias (i.e., PSE) that replicates and extends previous  
705 work (Sato, 2008; Reznik et al., 2015; Weiss et al., 2011a, 2011b) by showing that  
706 perceived intensity is reduced for self-generated sounds when they are presented at supra-  
707 threshold intensities, but enhanced when presented at near-threshold intensities.

708 Extant models disagree about how motor predictions affect the perceptual  
709 processing for expected action consequences. On one hand, consistent with ideomotor  
710 theories proposing that we internally activate the sensory outcome of our own action

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711 (Hommel et al., 2001), dominant cancellation models in the action literature have suggested  
712 that behavioural and neurophysiological responses to expected action effects are suppressed  
713 (i.e., lower PSE value and attenuated neural response; e.g., Blakemore et al., 2000; Kilteni  
714 et al., 2020; von Holst, 1954). Such attenuation is also predicted by preactivation accounts  
715 postulating that expectations preactivate representations of the predicted effects, increasing  
716 their baseline activity, thereby rendering the actual input less discriminable from baseline  
717 and reducing detection sensitivity (e.g., Roussel et al., 2013; Waszak et al., 2012). On the  
718 other hand, according to sharpening models, the motor-driven suppression proposed by  
719 cancellation theories is limited to units tuned away from the expected input, resulting in a  
720 sharpened population response and higher signal-to-noise ratio (SNR) that ultimately  
721 boosts detection sensitivity for what we expect (Yon et al., 2020; Yon & Press, 2017).  
722 However, none of these models can account for our findings: The cancellation account  
723 would predict lower perceived intensity irrespective of signal strength, while according to  
724 the preactivation and sharpening models we should have found significant differences in  
725 detection sensitivity (lower or higher for self-generated sounds, respectively). Critically,  
726 these models cannot explain the enhanced perceived intensity for expected sounds when  
727 presented at near-threshold intensities. Although this enhancement may be partly driven by  
728 multisensory integration processes that are known to boost processing when the unimodal  
729 signal is of low strength like the near-threshold self-generated sounds (e.g., inverse  
730 effectiveness; Stein & Meredith, 1993), two recent models have raised the possibility that  
731 the signal strength interacts with motor predictions in determining whether the processing  
732 of the expected events (i.e., self-generated sounds) will be enhanced or cancelled out (Press  
733 et al., 2020; Reznik & Mukamel, 2019).

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734           Reznik and Mukamel (2019) recently proposed that the inhibitory influence exerted  
735 by the motor cortex on auditory areas during motor acts (Schneider et al., 2018) may either  
736 dampen or enhance perceptual processing of self-generated sounds depending on the  
737 environmental context. According to their model, the motor-driven suppression of the  
738 auditory cortex (e.g., Buran et al., 2014; Carcea et al., 2017) leads to reduced activity at the  
739 population level, but also to more selective responses and thus higher SNR. Crucially,  
740 while net activity should be always reduced during motor engagement irrespective of  
741 intensity, the resulting SNR is proposed to be higher in faint compared to salient contexts.  
742 Faint stimulation is known to elicit responses only on “best-frequency” neurons, while  
743 louder stimuli also stimulate the neurons tuned to nearby frequencies (Reznik & Mukamel,  
744 2019). Thus, Reznik and Mukamel propose that in faint contexts, the global inhibition  
745 during motor engagement may result in “best-frequency” responses only, with almost  
746 complete silence of the activity in nearby frequencies thanks to the inhibition of the  
747 spontaneous activity, relatively enhancing the sound-evoked activity compared to the  
748 background noise (Buran et al., 2014; Carcea et al., 2017).

749           This proposal has two important implications as concerns the consequences of  
750 motor engagement in perceptual processing: First, salient environments would be  
751 characterized by reductions in the loudness perception that are proposed to be driven by  
752 reduced population activity. Yet, no predictions are made as to whether perceived intensity  
753 for near-threshold sounds would be also attenuated or not, thus leaving unexplained our  
754 finding that perceived intensity is enhanced for self-generated near-threshold sounds.  
755 Second, the increased SNR would boost the detectability of near-threshold sounds only,  
756 since in salient contexts sensitivity is already at ceiling. The authors found support for this

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757 claim in the study by Reznik et al., (2014), where self-generation significantly enhanced  
758 sound detectability. However, this finding was not replicated in the present study.

759         A caveat to the model proposed by Reznik & Mukamel is that it is largely based on  
760 animal studies that compared auditory responses in active vs. passive states (i.e.,  
761 locomotion vs. quiescence or Go/No-Go tasks; e.g., Buran et al., 2014; Carcea et al., 2017),  
762 rather than comparing self- vs. externally-generated sounds. It is very likely that active  
763 states and contingent action-stimulus relationships do not have the same underlying  
764 mechanisms, and that they in turn do not modulate perception in the same way. The  
765 modulations found in active states may be mostly driven by unspecific neuromodulatory  
766 processes (i.e., arousal; McGinley et al., 2015), while in the presence of a contingent  
767 action-stimulus relationship specific prediction mechanisms may dominate (i.e., corollary  
768 discharge). This critical difference may explain why we did not find any significant effects  
769 in the detection task that lacked a contingent press-sound relationship (only 50% of the  
770 presses generate a sound). However, previous detection paradigms have also reported no  
771 such enhancement (Myers et al., 2020; McGinley et al., 2015; Neske et al., 2019), thus  
772 raising the possibility that the low power of the only human study reporting lower detection  
773 thresholds for self-generated sounds (n = 10; Reznik et al., 2014) may have reduced the  
774 likelihood of their statistically significant result reflecting a true effect (Button et al., 2013).  
775 Collectively, although Reznik and Mukamel were the first to attempt to explain how sound  
776 intensity may modulate neural and behavioural responses during motor engagement, their  
777 model cannot fully explain our findings, and in particular it also cannot explain why the  
778 interactive effects we observed here are limited to perceptual bias, rather than perceptual  
779 sensitivity.

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780           We believe that our findings can be best explained by the opposing process theory  
781 which highlights the role of signal strength in enhancing or suppressing the processing of  
782 predictable stimuli (Press et al., 2020). According to this theory, perception is in principle  
783 biased towards expected stimuli, such as self-generated and thus more predictable stimuli.  
784 However, if the presentation of an unpredicted stimulus generates a high level of surprise  
785 after the initial stages of sensory processing, then the perceptual processing of this  
786 surprising stimulus is boosted. In terms of self-generation effects, this would imply  
787 enhanced processing of externally-generated, and thus unpredictable (surprising) stimuli.  
788 Critically, however, the level of surprise is closely related to signal strength, as surprise  
789 reflects both the distance between the prior and posterior distributions, as well as their  
790 precision (Kullback-Leibler divergence, KLD; Kullback, 1959; Itti & Baldi, 2009), and  
791 weaker signals are inherently less precise. For example, the sound of a horn in the middle  
792 of the night would elicit surprise but only if it is loud, and thus clearly audible. In sum,  
793 according to this view, supra-threshold externally-generated stimuli are inherently more  
794 surprising than the self-generated ones, shifting perception toward the unexpected (i.e.,  
795 enhanced perceived loudness for the externally-generated sounds at supra-threshold  
796 intensities). Conversely, when sounds are presented at a near-threshold intensity, the  
797 increased uncertainty and higher level of noise in the signal renders externally-generated  
798 sounds unsurprising and perception is shifted towards the expected (i.e., enhanced  
799 perceived intensity for the self- compared to the externally-generated sounds at near-  
800 threshold intensities). Thus, the surprise-driven mechanism operates only for highly precise  
801 and therefore task-relevant unexpected signals, triggering a process that boosts their  
802 perception by driving attention away from the consequences of self-made acts as proposed  
803 by the active inference framework (Brown et al., 2013). Therefore, the shifts in perceived

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804 intensity in either direction may be related to surprise-induced attentional mechanisms that  
805 have been suggested to modulate the precision of the prediction error, rather than the  
806 prediction error itself (Barron et al., 2020; Brown et al., 2013). Nevertheless, one would  
807 expect that this mechanism would also operate in detection paradigms, contrary to the null  
808 findings obtained in the detection task. While these findings may be due to the lack of a  
809 contingent action-sound relationship as mentioned before, an alternative explanation is that  
810 the attentional nature of these effects results in affecting certain aspects of perceptual  
811 processing.

812         The studies conducted so far have not systematically assessed the effects of self-  
813 generation (and their interaction with stimulus intensity) on the different perceptual  
814 measures. Discrimination studies have only reported shifts in the PSE, a measure of  
815 *perceptual bias*, while JND – a measure of *perceptual sensitivity* – remains unaffected by  
816 self-generation (Desantis et al., 2016; Kilteni et al., 2020; Sato, 2008; Weiss et al., 2011a,  
817 2011b). Conversely, studies employing detection tasks, have typically measured perceptual  
818 thresholds or the  $d'$  score (*perceptual sensitivity* measures), and criterion (Cardoso-Leite et  
819 al., 2010; Reznik et al., 2014), which reflects the *response bias*. Here, we provide a more  
820 complete picture of how motor actions may affect perception by having two tasks that  
821 allowed us to obtain all these measures within subjects and show that the effects of self-  
822 generation and their interaction with stimulus intensity are driven by shifts in *perceptual*  
823 *bias*. This is further supported by the correlation analyses across the two tasks that yielded  
824 significant correlations only between detection thresholds and JND, both being measures of  
825 *sensitivity*, but not with *perceptual bias* measures, such as PSE. Collectively, our study  
826 points to the effects being limited to *perceptual bias*, rather than *sensitivity* measures.

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827           In sum, the present study showed that the intensity of the sensory feedback biases  
828 perception for self-initiated stimuli in a differential manner, with attenuated perceived  
829 loudness at supra-threshold intensities, but perceptual enhancement for near-threshold ones.  
830 These findings provide empirical support to the opposing process theory (Press et al., 2020)  
831 by showing that the behavioural difference between self- and externally-generated sounds  
832 interacts with the noise of the sensory outcome in driving perceptual processing. The  
833 strength of this study is that it extends previous work by demonstrating that self-generation  
834 and its interaction with intensity only affects *perceptual bias*, rather than *perceptual*  
835 *sensitivity* (Myers et al., 2020; Sato, 2008; Weiss et al., 2011a, 2011b) or *response bias*  
836 (Reznik et al., 2014). Although the opposing process theory does not clarify whether  
837 expectation effects are driven by perceptual or later decisional processes (Press et al.,  
838 2020), we argue that the proposed bias in perception as a function of signal strength implies  
839 a competition between two percepts, which was only the case in the discrimination task and  
840 may point to attentional processes that are known to reverse the effects of prediction on  
841 behavioural and neural processing (Kok et al., 2012). We believe that further behavioural  
842 and neurophysiological work is required to replicate these findings, assess the  
843 neurophysiological correlates of these effects, as well as the influence of other factors such  
844 as arousal, that are also known to affect behavioural performance (Kuchibhotla et al., 2017;  
845 McGinley et al., 2015), and ultimately provide a comprehensive account of how motor  
846 predictions and signal strength shape the perception of our environment.

#### 847 **CRedit authorship contribution statement**

848 NP and ISM designed the study; NP programmed the task and collected and analyzed the  
849 data; NP and ISM wrote the manuscript; ISM supervised the project.

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854



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