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## When does vagal activity benefit to the discrimination of highly overlapping memory traces?

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1                   **When does vagal activity benefit to the discrimination of highly**  
2   **overlapping memory traces?**

3  
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20

21 **Abstract (max 250 words)**

22 Distinguishing among similar events is indeed crucial to memory. In a dangerous context, this  
23 ability may be less essential, whereas in a secure context it may provide an adaptive  
24 advantage notably in social situations. Vagal activity as a marker of the individual's adaptation  
25 in social engagement contexts might predict the ability to discriminate highly similar memories  
26 in an unthreatening context. The present study aims to test the relation between vagal activity  
27 and memory discrimination by manipulating the visual distinctiveness of stimuli (high *vs.* low)  
28 in an ecological memory discrimination task with humanoid characters. It was expected that  
29 vagal activity support adaptive self-regulatory processes which may be needed only when the  
30 memory discrimination is challenging (low distinctiveness between true memory and lure). In  
31 a study phase, multiple realistic fictional humanoid characters performed the same action on  
32 different objects. The characters could be very similar or very distinct one to each other. Then,  
33 during a test phase, the participants had to discriminate whether a displayed character on the  
34 screen was exactly matched the one performing the given action on a specific object in the  
35 study phase (target). Vagal activity was assessed in undergraduate students ( $n = 40$ ) before the  
36 study phase. Higher vagal activity predicted better memory discrimination performance  
37 specifically when the distinctiveness between the lure and target was low. These data extend  
38 previous work on vagal activity and memory suggesting that heart-brain interactions represent  
39 an adaptive psychophysiological mechanism underlying memory discrimination specifically  
40 when it is challenging in an unthreatening context.

41

42 **Keywords:** autonomic nervous system, heart rate variability, memory discrimination, memory  
43 retrieval, pattern separation

44

45

## 46 **Introduction**

47 Vagal activity is a marker of the individual's adaptation in social engagement contexts (Porges,  
48 2007). Vagal activity is measured by recording the fluctuation in time intervals between  
49 succeeding heart beats over time, namely heart rate variability (Shaffer, McCraty, & Zerr,  
50 2014). According to the polyvagal theory (Porges, 2007), self-regulatory processes enabling  
51 social engagement are underpinned by outflow and functional organization of vagus nerve  
52 while sympathetic activity primes cognitive processes associated with "*fight or flight*"  
53 responses. Vagally-mediated heart rate variability (vmHRV) is logically associated with  
54 performance on goal directed tasks requiring adaptive regulation and inhibitory control (see  
55 Forte, Favieri, & Casagrande, 2019 for a review), whereas tasks inducing mental stress (e.g.  
56 certain working memory tasks) are associated with decreased vmHRV (Park, Vasey, Bavel, &  
57 Thayer, 2014; Thayer & Sternberg, 2006).

58

59 Memory also plays a crucial role both for survival (Scofield, Buchanan, & Kostic, 2018) and  
60 social interactions (Tzakis & Holahan, 2019). Therefore, only in the latter case should memory  
61 rely on vmHRV since a stress-free social context should promote vagal activity. To date, only  
62 one study has reported that vmHRV predicts memory performance (Feeling et al., 2021). The  
63 relationship was found in the sole case of memory discrimination between true (target) and  
64 semantically related lures, but not with memory performance *per se*. Distinguishing among  
65 similar events is indeed crucial to memory (Stevenson, Reagh, Chun, Murray, & Yassa, 2020).  
66 Otherwise, new information would overwrite similar memories previously learned  
67 (catastrophic interference, Yassa & Stark, 2011). This ability is probably not essential in  
68 stressful situations since distinguishing a tiger from a leopard does not matter as far the flight  
69 response is activated. On the contrary, this ability might be crucial in stress-free situations, as  
70 for instance in a social context in which recognizing the face of a friend within a crowd would

71 bring direct social benefits. Accordingly, rapid visual detection of threats rely on automatic  
72 processing of their coarse visual features (Lojowska, Mulckhuysse, Hermans, & Roelofs, 2019)  
73 while vagal is associated with facial recognition (Park & Thayer, 2014). Regarding memory  
74 discrimination, distinguishing highly similar memory traces should also only be relevant in an  
75 unthreatening context. Therefore, vagal activity should bring an adaptative advantage to  
76 memory discrimination in other types of stress-free situations and unthreatening contexts, as  
77 for instance when distinguishing memory traces of people performing certain actions. This  
78 advantage should logically (according to this evolutionist perspective) only be observed in a  
79 situation where discrimination is challenging – that is, when a strong overlap exists between  
80 the memory traces. The present study aims to test this specific hypothesis in an ecological  
81 visual memory task.

82

## 83 **Method**

### 84 **Participants**

85 Forty-seven undergraduate psychology students were enrolled in a larger study focusing on the  
86 impact of a breathing exercise on decision-making. They all completed an exhaustive screening  
87 (interview and questionnaires) to ensure that they had no condition which may interfere with  
88 cardiac and cognitive functioning (see Supplementary materials and Magnon, Dutheil, &  
89 Vallet, 2021). Sociodemographic data (age, sex, etc.) and medical histories that may affect  
90 cognition and cardiovascular functioning, such as neurological (head trauma, epilepsy...),  
91 physiological (hypo- or hyperthyroidism, type 2 diabetes...) or neurodevelopmental factors  
92 (autism, dyslexia...). Lifestyle factors, such as binge drinking alcohol (more than five  
93 consecutive alcoholic drinks in the last week) and high body mass index ( $BMI \geq 30$ ), likely to  
94 influence HRV also served as exclusion criteria. Depression and anxiety were assessed by the  
95 Hospital and Anxiety Depression Scale (HADS, see Zigmond & Snaith, 1983). Two

96 participants were excluded due to a high depression/anxiety score and 1 due to active  
97 medication. Four more participants were excluded due to flattened heart rate recordings  
98 (wristband too loose for comfort reasons). The final sample thus consisted of 40 participants  
99 ( $M_{Age}= 19.76$ ,  $SD_{Age}= 1.50$ , 5 men). The research was approved by the Île-de-France Ethics  
100 Committee (2021-A01735-36).

101

## 102 **Material**

### 103 **HRV assessment**

104 The EMPATICA E4 Wristband (Empatica E4, Italy) was used to assessed HRV. This medical-  
105 grade wearable device was validated in comparison to electrocardiography (Schuurmans et al.,  
106 2020). Heart rate was recorded during the whole session and the inter-beat intervals were  
107 extracted (as recommended, Li, Rüdiger, & Ziemssen, 2019) during the test phase of the  
108 memory discrimination task (more specifically the last 5 minutes of the test phase) whether the  
109 task was administrated before or after the breathing exercise (see procedure). A visual check  
110 ensured the quality of the recordings as the control of artefacts or occasional ectopic beats. A  
111 very low threshold filter was applied when judged necessary. Kubios (v.3.3.1) was used to  
112 compute the High Frequency (HF, range from 0.15 to 0.4 Hz) power. This is most reliable  
113 vmHRV index (as others might be affected by sympathetic activity, see Berntson, Lozano, &  
114 Chen, 2005), which is the percentage of HF among the total power minus the very low  
115 frequency (normal units) (Laborde, Mosley, & Thayer, 2017; Tarvainen, Niskanen, Lipponen,  
116 Ranta-Aho, & Karjalainen, 2014).

117

### 118 **Memory discrimination task**

119 Fourteen blocks (2 practice blocks, 12 experimental blocks) of 4 characters each were created  
120 (for a total of 48 trials) using The Sims 4<sup>TM</sup> video game. The distinctiveness of the characters

121 was configured according to 11 dimensions: gender (man *vs.* woman), build (heavy *vs.* light),  
122 skin color (blue, red...), age (child *vs.* adult), hair color (blond, brown...), head covering  
123 (beanie, beret...), glasses (with *vs.* without), sleeve length (short *vs.* long), pant length (short  
124 *vs.* long), shoes (sneakers *vs.* flip-flops), and faces. In the "LOW DISTINCTIVENESS" blocks,  
125 the characters in each block were visually lowly distinct from each other (several dimensions  
126 were identical, see Figure 1). More precisely, within each block in the LOW  
127 DISTINCTIVENESS condition, 5 dimensions (gender, build, skin color, age, hair color) were  
128 identical for the 4 characters of a given block (the 6 remaining were pseudorandomized across  
129 the 4 characters within the block). In the "HIGH DISTINCTIVENESS" condition, the  
130 characters in each block were visually highly distinct from each other (11 dimensions were  
131 pseudorandomized across the 4 characters within the block). Twelve types of action were  
132 selected (e.g., sitting on, playing, etc.) to be performed on the 4 chosen objects per block (e.g.,  
133 a chair, a stool...). Within each block, the four characters performed the same action, but on a  
134 different object. A given action (e.g., sitting on) was provided in the LOW  
135 DISTINCTIVENESS condition for half of the participants, and in the HIGH  
136 DISTINCTIVENESS condition for the other half of the participants. The selected actions are  
137 realistic and socially relevant (a humanoid character sitting on a chair). Each action was  
138 presented in a video format lasting approximately 8 seconds (see Figure 2 for details on the  
139 task's administration). After a 400ms fixation cross, a voice stated the current action and an  
140 object on which the action was performed while a video showing a character performing the  
141 action was played. The participants have to memorize the appearance of a character, the type  
142 of action and the object on which the action was performed on. The videos in the LOW and  
143 HIGH DISTINCTIVENESS blocks were counterbalanced across participants (using two lists,  
144 see Supplementary materials for more details on this task). After the study phase, a filler task  
145 (mental arithmetic) occurred before the test phase, one of the audio tracks from the study phase

146 was replayed with a neutral grey background screen for 3,000ms. A photograph of one of a  
147 character of the corresponding action's block was then displayed with a black background for  
148 1,000ms or until the participant's responded. Finally, an Inter-Trial Interval (ITI) of 2,000ms  
149 was used before the next trial started. The participants had to decide whether the character  
150 shown corresponded exactly to the character who performed the action on the specific object  
151 (learned in the study phase) by using the keyboard to answer "MATCH" or "MISMATCH" as  
152 accurately and quickly as possible. In the "MISMATCH" condition, the displayed character  
153 was from the same action's block and had performed the same action, but not on the targeted  
154 object stated by the voice. In the "MATCH" condition, the character was the same as the  
155 character who had performed the action on the object mentioned in the audio description. The  
156 characters were presented only once either in the "MISMATCH" or in the "MATCH"  
157 conditions. Accuracy and response times for each trial were collected. This task is considered  
158 as robust giving similar results in several studies of our lab (Purkart, Mille, Versace, & Vallet,  
159 2021). As discrimination performance was the variable of interest, the main outcome of this  
160 task was accuracy.

161

## 162 **Procedure**

163 Each participant was tested individually in a session that last 1 hour. Firstly, the Empatica  
164 wristband was installed on the left wrist of the participant and turned on. During a 10-minute  
165 rest period, health and sociodemographic data were collected. Then, participants completed  
166 either a decision-making task or the memory discrimination task (~~Supplementary materials~~)  
167 lasting approximately 10 minutes. Afterward, the participants underwent a 5-minute breathing  
168 exercise followed by the completion of the other computerized task counterbalanced with the  
169 first one described above (either the memory discrimination task or the decision-making task).  
170 After the HADS and other questionnaires (Supplementary materials), the session ended by a

171 debriefing. This design was chosen to maximize the variability of HF to serve as assessed  
172 during the memory discrimination test. In this way, the participants who completed the memory  
173 task after the deep and slow breathing should have higher HF than some participants who  
174 performed it before. These choices allow to greatly diminish the sample size requirements (see  
175 Magnon, Dutheil, et al., 2021 for a similar procedure in a previous study).

176

### 177 **Statistical analyses**

178 All the statistical analyses were performed with the R statistical software package (v4.0.2,  
179 RStudio Team, 2020). The significance threshold was set at  $p < .05$ . An analysis of variance  
180 with Time (memory discrimination task completed before vs. after the breathing exercise)  
181 confirmed that participants who completed the memory task after the breathing exercise had  
182 higher HF power level. To test whether vmHRV is positively associated with memory  
183 discrimination specifically in the LOW DISTINCTIVENESS condition, an interaction was  
184 tested between HF power as a continuous predictor and DISTINCTIVENESS (LOW vs.  
185 HIGH) as a categorical predictor and the memory discrimination index A' (or area under the  
186 curve) as dependent variable. Then, to explore further the specificity of the effect, a linear  
187 regression with HF power as the predictor and the A' index as dependent variable in both LOW  
188 and HIGH DISTINCTIVENESS was performed. Assumptions for linear regression were  
189 checked with the R package “car” (Fox et al., 2021) and an outlier detection was performed as  
190 well revealing no outliers or influential data (the only value detected was not influential,  $p$   
191 = .08). To ensure the validity of our findings, we conducted robust (to outliers) interaction  
192 analyses and linear regressions using the R package “MASS” (Ripley et al., 2022). Because  
193 traditional linear regressions are highly sensitive to outliers and influential data, robust  
194 regressions are specifically designed to overcome these limitations while maintaining the

195 sample size (Yu & Yao, 2017). The A' index<sup>1</sup> is based on the signal detection theory  
196 (Macmillan & Creelman, 2005):

197 
$$A' = \frac{1 - (\text{falsealarms}/\text{hits}) + (\text{omissions}/\text{correctrejections})}{4}$$

198 The lower is the A', the poorer is the discrimination performance. A' is robust and widely used  
199 discrimination index (Pastore, Crawley, Skelly, & Berens, 2003) especially for memory  
200 discrimination (see Reagh et al., 2014), recognized for its validity (Stanislaw & Todorov,  
201 1999).

202

### 203 **Results**

204 As expected, the interaction term between HF power and DISTINCTIVENESS (LOW vs. HIGH,  
205 see Table 1 for descriptive statistics) accounted for a significant proportion of the variance in  
206 the memory discrimination score A' ( $F(1, 38) = 4.17, p = .04, R^2 = .21$ ). Furthermore, a linear  
207 regression analysis revealed that HF level explained a significant amount of the variance in A'  
208 index in the LOW DISTINCTIVENESS condition ( $F(1, 38) = 5.81, p = .02, R^2 = .11$ ). HF  
209 level positively predicted *discrimination performance A'* ( $\beta = .005, p = .02, \text{ see Figure 3}$ ). In  
210 *contrast*, a linear regression analysis showed that HF level did not explain a significant amount  
211 of the variance in A' index in the HIGH DISTINCTIVENESS condition ( $F(1, 38) = -.0005,$   
212  $p > .10, R^2 = .02, \text{ see Figure 4}$ ).

213

214

215

216

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1 With hits = answering “match” when the character shown was the one performing the given action asked; correct rejections = answering “mismatched” when the character shown is different; false alarms = answering “match” when the character shown in the test phase does not exactly match the character performing the action in the study phase; omissions = answering “mismatch” when the character shown during the test phase is exactly the same.

217 **Table 1**

218 Mean (SD) of the discrimination performance index  $A'$  in the HIGH and LOW  
219 DISTINCTIVENESS conditions.

<i>Distinctiveness level</i>	<i>HIGH</i>	<i>LOW</i>
$A'$	0.74 (0.15)	0.57 (0.23)

220

221 **Discussion**

222 The present study aimed to explore whether vmHRV provides a benefit to memory  
223 discrimination only when the stimuli are highly overlapping as predicted by the polyvagal  
224 theory (Porges, 2007). The vagus nerve has indeed been considered as a maker of one's ability  
225 to self-regulate and to adjust to new situations and environments in social context (Porges,  
226 2007; Thayer, Hansen, Saus-Rose, & Johnsen, 2009). As highly overlapping lures are more  
227 challenging to discriminate, this process might require self-regulatory adaptative processes  
228 associated with vmHRV which would not be needed for lowly overlapping lures. Such  
229 discrimination appears crucial in social contexts compared to stressful/survival situations in  
230 which fast gist impressions should direct the individual's reactions (Scofield et al., 2018).

231

232 As expected, higher vmHRV predicted better memory discrimination performance but only  
233 when the distinctiveness between lures and targets was low. Those results indicate that vmHRV  
234 is not always required to discriminate lures from hits as previously suggested (Feeling et al.,  
235 2021). This result could be applied to cognitive aging in which memory performance is  
236 particularly related to discrimination (Mille, Brambati, Izaute, & Vallet, 2021). Maintaining an  
237 elevated vmHRV on the long-term might promote the discrimination of highly overlapping  
238 memory traces across the lifespan (Magnon et al., In revision). Accordingly, intervention that  
239 stimulates vagal activity could prove beneficial to prevent memory aging. Supporting this  
240 hypothesis, it was previously reported that transcutaneous vagus nerve stimulation enhances

241 associative memory performance in older individuals (Jacobs, Riphagen, Razat, Wiese, &  
242 Sack, 2015), which highlights the relevance of studying heart-brain interactions to promote  
243 healthy aging. Should high vagal activity be found to prevent memory impairment with age, a  
244 simple 5-minute breathing exercise that seems sufficient to increase vagal activity in the elderly  
245 (Magnon, Dutheil, et al., 2021) could be a promising, cheap and simple clinical lead to promote  
246 successful cognitive aging.

247 While many factors were controlled to ensure internal validity, several lifestyle factors that  
248 might influence HRV or cognition were not assessed, such as the practice of physical activity  
249 and sedentariness (Magnon, Vallet, & Auxiette, 2018; Magnon, Vallet, Dutheil, & Auxiette,  
250 2021). Furthermore, the sample for this exploratory study is relatively small. However, the  
251 design chosen proves to be efficient in increasing variability in vmHRV by using a validated  
252 breathing exercise reducing sample size requirements (Magnon, Dutheil, et al., 2021). Finally,  
253 despite the validated reliability and accuracy of the medical-grade wristband (Schuurmans et  
254 al., 2020), the wristband remains relatively less accurate than an electrocardiogram.

255

256 To conclude, the present study replicates and extends the results of the sole study on the  
257 association between HRV and memory discrimination. The distinctiveness manipulation  
258 between lures and targets indicates that vagal activity is only associated with highly  
259 overlapping memory traces corresponding to challenging social situations. Future studies are  
260 required to further investigate this relationship with its neural dynamic during memory  
261 discrimination. If heart-brain interactions are proven to be involved in memory discrimination,  
262 then vagal stimulation, through breathing exercises for instance, might constitute a simple and  
263 cheap cognitive intervention.

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273 **Author contributions**

274 VM and JM conceived the study. VM designed the protocol and wrote the first version of the  
275 manuscript. GTV supervised the conception of the study. JM and RP created the visual  
276 discrimination memory task. VM, JM, RP and GTV analyzed the data and interpreted the  
277 results. FD and PC gave their insight and expertise for the HRV measure and analyses. All  
278 authors participated in the critical revision of the article. All authors read and approved the  
279 final version.

280

281 **Data Availability Statement**

282 The data used in the present article are available at

283 <https://mfr.osf.io/render?url=https://osf.io/pxrcn/?direct%26mode=render%26action=downlo>  
284 [ad%26mode=render](https://mfr.osf.io/render?url=https://osf.io/pxrcn/?direct%26mode=render%26action=downlo)

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### LOW DISTINCTIVENESS



### HIGH DISTINCTIVENESS

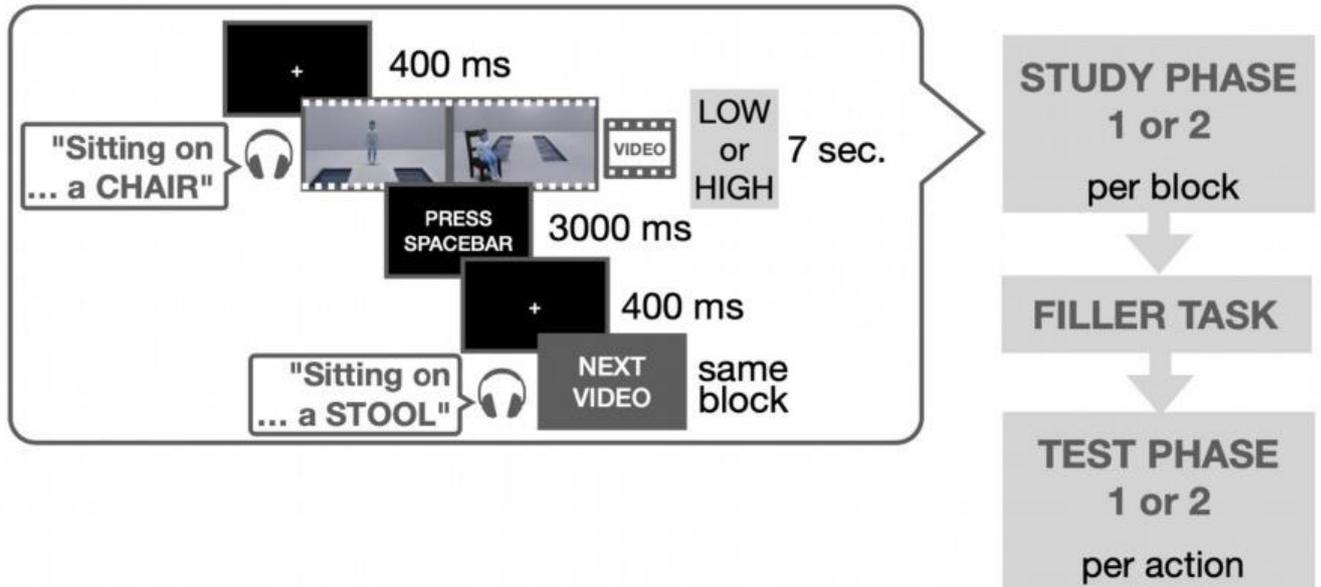


388

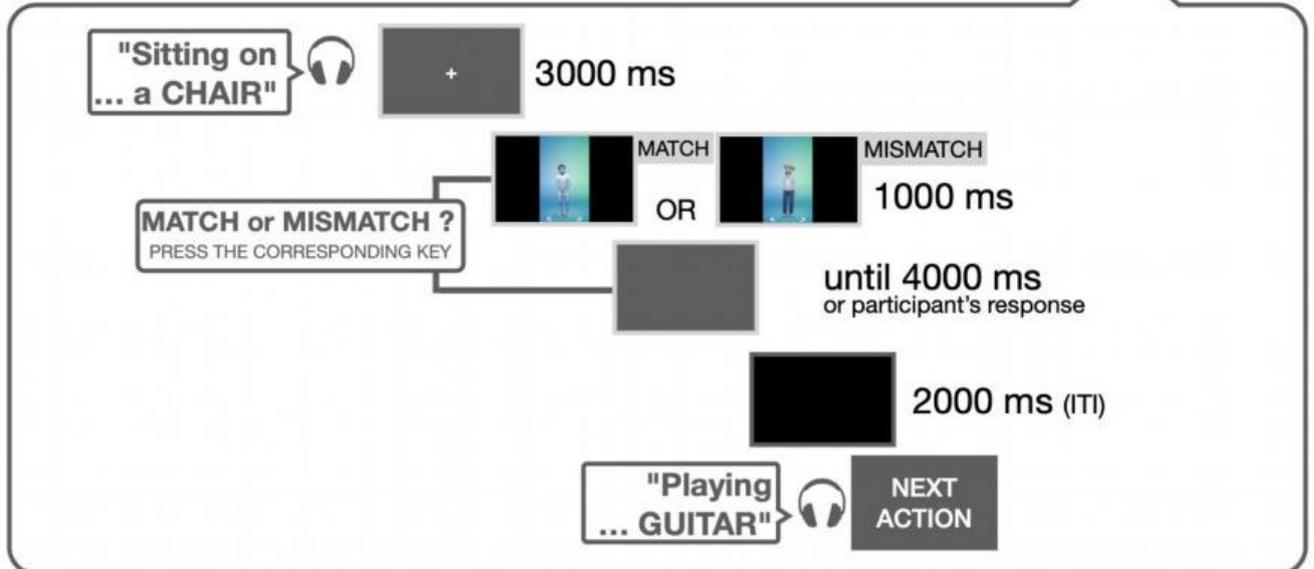
389

390 **Fig. 1.** Photographs of characters in a block for each distinctiveness condition.

one trial



one trial



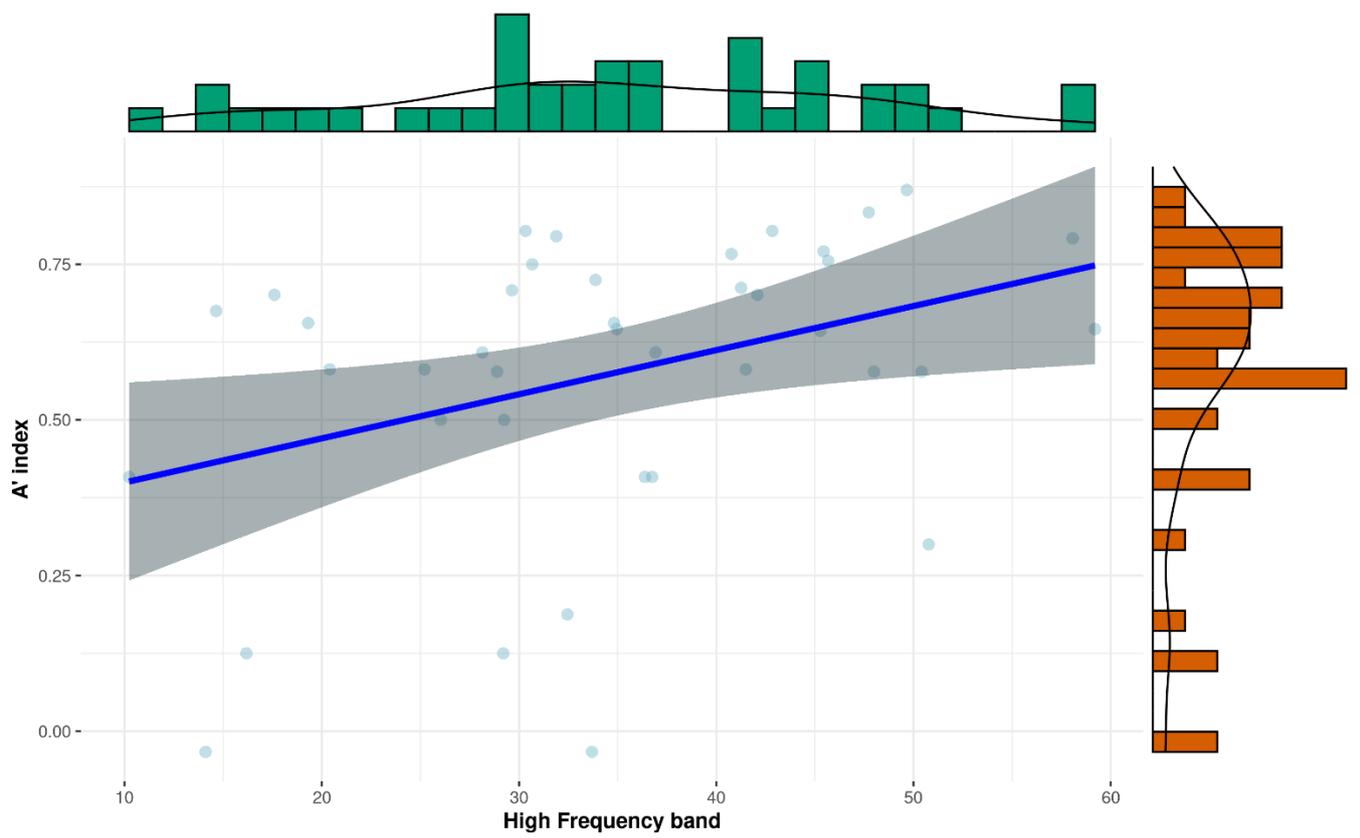
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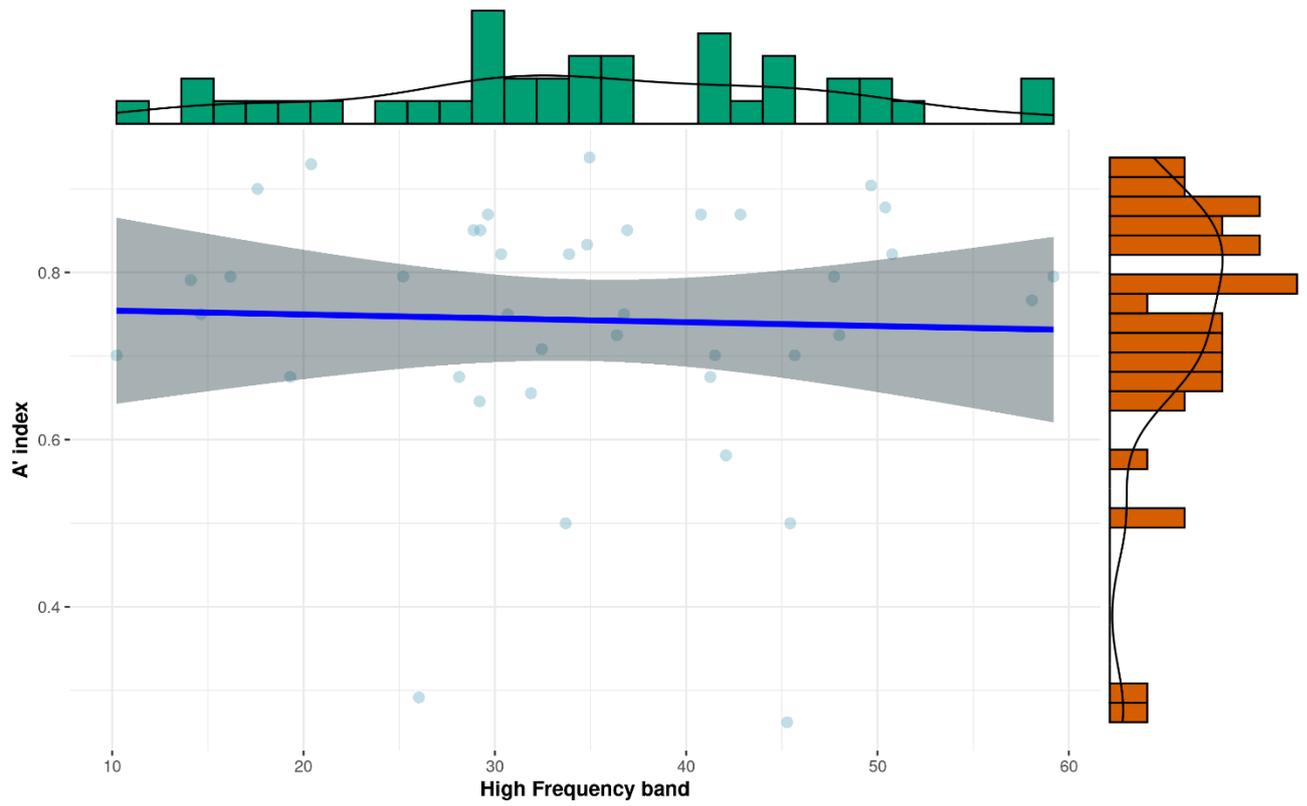
393 **Fig. 2.** Procedure and details of the memory discrimination task.

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**Fig. 3.** The relationship between vmHRV (HF level) and discrimination performance (A') in the LOW DISTINCTIVENESS condition.



**Fig. 4.** The relationship between vmHRV (HF level) and discrimination performance (A') in the HIGH DISTINCTIVENESS condition.