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Temporal characteristics of global form perception in translational and circular Glass patterns

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(Article begins on next page)

1 **Temporal characteristics of global form perception in translational and circular**  
2 **Glass patterns**

3  
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35 **Abstract**

36 The human visual system is continuously exposed to a natural environment with static and moving  
37 objects that the visual system needs to continuously integrate and process. Glass patterns (GPs) are  
38 a class of visual stimuli widely used to study how the human visual system processes and integrates  
39 form and motion signals. GPs are made of pairs of dots that elicit a strong percept of global form. A  
40 rapid succession of unique frames originates dynamic GPs. Previous psychophysical studies  
41 showed that dynamic translational GPs are easier to detect than the static version because of the  
42 spatial summation across the unique frames composing the pattern. However, it is not clear whether  
43 the same mechanism is involved in dynamic circular GPs. In the present study, we  
44 psychophysically investigated the role of the temporal and spatial summation in the perception of  
45 both translational and circular GPs. We manipulated the number of unique frames in dynamic GPs  
46 and the update rate of the frames presentation. The results suggest that spatial and temporal  
47 summation across unique frames takes place for both translational and circular GPs. Moreover, the  
48 number of unique frames and the pattern update rate equally influence the discrimination thresholds  
49 of translational and circular GPs. These results show that form and motion integration is likely to be  
50 processed similarly for translational and circular GPs.

51

52 **Keywords:** Translational Glass patterns, circular Glass patterns, dynamic Glass patterns, form-  
53 motion interaction, temporal summation, apparent motion

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69 **1. Introduction**

70 Glass patterns (GPs) (Glass, 1969) are visual patterns widely used in psychophysical  
71 research to study how form and motion mechanisms interact in human and non-human primates'  
72 visual cortex (Kourtzi et al., 2005, 2008; Krekelberg et al., 2003, 2005; Lewis et al., 2002; Wilson  
73 et al., 2003, 2004; Wilson & Wilkinson, 1998). GPs are composed of dot pairs (dipoles) whose  
74 orientations align to create a global form; by applying different geometric transformations, it is  
75 possible to change the spatial relationship between dipole orientations to create visual textures that  
76 convey the perception of specific global forms such as radial, circular, or spiral patterns.

77 GPs can be static and dynamic. Static GPs are made of a single unique frame, whereas dynamic  
78 GPs are made of multiple independent frames, each containing a GP with randomly placed dipoles  
79 showed in rapid succession. Usually, for each new frame, a new spatial arrangement of the dipoles  
80 is created while the orientation remains constant. In dynamic GPs, the rapid succession of frames  
81 induces the perception of apparent motion along the pattern's orientation axis even though there is  
82 no dipole-to-dipole correspondence between successive frames. Therefore, no coherent motion is  
83 present in this class of stimuli (Nankoo et al., 2012; Pavan et al., 2017; Ross, Badcock & Hayes,  
84 2000). In general, dynamic GPs are more easily detected and discriminated than static GPs (Burr &  
85 Ross, 2006; Nankoo et al., 2012, 2015; Or et al., 2007; Pavan et al., 2017, 2019). For static patterns,  
86 circular GPs exhibit lower detection or discrimination thresholds than translational GPs, a finding  
87 that has been attributed to the activity of concentrically tuned units in cortical area V4 (Wilson,  
88 Wilkinson, & Asaad, 1997; Wilson & Wilkinson, 1998). However, Dakin and Bex (2002) showed  
89 that the advantage of circular GPs over translational GPs may be due to the strong influence of the  
90 pattern edge (i.e., the aperture window) rather than the intrinsic statistical properties of the pattern.  
91 Dakin and Bex (2002) found that higher thresholds for translational GPs were correlated with the  
92 unmatched circular aperture of the patterns. On the other hand, Anderson and Swettenham (2006)  
93 using circular, radial, and translational (horizontal) GPs within a square aperture, found that both  
94 strabismic amblyopes and control participants showed a better detection performance for radial and  
95 circular GPs than translational GPs. Similarly, Kelly et al. (2001) measured the detection thresholds  
96 of circular, radial, and translational (vertical and horizontal) GPs, all presented in a square aperture.  
97 The authors found that participants better discriminated circular and radial GPs than translational  
98 GPs, despite the square aperture. Therefore, most of the studies report that the aperture window of  
99 GPs does not influence participants' detection thresholds.

100 Ostwald et al. (2008) using fMRI and different GP types presented in circular apertures,  
101 showed a continuum in the integration process from selectivity for local orientation signals in early  
102 visual areas, to selectivity for global form in higher occipitotemporal areas. Using multivoxel

103 pattern analysis (MVPA) the authors found that high-level occipitotemporal areas distinguish  
104 differences in global form, rather than low-level stimulus properties, with higher accuracy than  
105 early visual areas, consistent with the hypothesis of global pooling mechanisms of local orientation  
106 signals. Besides, classification accuracy in early visual areas (e.g., V1 and V2) was similar for all  
107 the GPs used (translational, radial, and concentric patterns), though the lateral occipital complex  
108 (LOC) exhibited higher classification accuracy for all the patterns.

109 Apparent motion evoked by dynamic GPs has been explored by various studies (Day &  
110 Palomares, 2014; Donato et al., 2020; Nankoo et al., 2012, 2015; Pavan et al., 2017; Ross, 2004).  
111 For example, Ross et al. (2000) found that the perception of apparent trajectory in dynamic GPs is  
112 particularly evident at high pattern update rates (i.e., when frames are presented in rapid  
113 succession). Moreover, the authors showed that the apparent motion in dynamic GPs is created by  
114 integrating form information in the dipoles among frames. Interestingly, there is neuroimaging  
115 evidence that shows that the human brain, in particular the human motion complex hMT+, responds  
116 similarly to apparent/non-directional motion generated by form cues and real/directional motion  
117 generated by motion cues, a feature called ‘*cue invariance*’ (Krekelberg et al., 2005).

118 Furthermore, Day and Palomares (2014) investigated whether the change of the update rate  
119 in dynamic circular GPs affected global form perception. They used six different update rates (i.e.,  
120 1, 2, 4, 8, 18, and 36 Hz). Participants had to discriminate whether the coherent circular GP was  
121 presented in either the first or second temporal interval (two-interval forced-choice task; 2IFC task).  
122 The authors found that an increased update rate in dynamic GPs was correlated to improved  
123 participants’ performance in GP detection. In conclusion, the temporal features of dynamic GPs are  
124 fundamental for the perception of apparent/non-directional motion. This finding supports the idea  
125 that temporal and form information (i.e., dipoles’ orientation) in GPs is summed to increase the  
126 observer’s sensitivity to the dynamic GPs.

127 Subsequently, Nankoo et al. (2012) assessed the detection thresholds of apparent and real  
128 motion generated by different types of GPs and random dot kinematograms (RDKs). The authors  
129 estimated and compared detection thresholds for radial, translational (horizontal and vertical),  
130 concentric and spiral patterns for static and dynamic GPs and RDKs. The results showed lower  
131 detection thresholds for dynamic GPs and RDKs than static GPs. However, detection thresholds of  
132 dynamic GPs had a similar trend to static GPs instead of RDKs. These results suggest that both  
133 types of GPs seem to be processed mainly by their form cues. This points to different neural  
134 mechanisms underlying GPs and RDKs. A possible reason why dynamic GPs have lower detection  
135 or discrimination thresholds than static GPs is that as soon as the update rate of dynamic GP  
136 increases, the number of frames also increases (Day & Palomares, 2014). This might induce a

137 temporal summation of local signals into a global percept that favors detection and discrimination  
138 processes. However, it remained unclear whether the enhanced sensitivity of dynamic GPs is to be  
139 attributed only to the temporal integration of local signals of the visual pattern (producing apparent  
140 and non-directional motion) or also to the summation of form signals occurring across multiple  
141 frames. This has been further investigated by Nankoo et al. (2015) in a psychophysical experiment  
142 where the authors used static and dynamic translational GPs. The rationale was that if the lower  
143 thresholds observed for dynamic GPs are due to the summation of multiple form signals, a linear  
144 decrease in threshold would be expected as the number of frames increases. Furthermore, given that  
145 each GP in the sequence producing dynamic GPs is presented for a short duration with respect to  
146 the single GP in the static pattern, the authors measured discrimination thresholds for GPs that  
147 contained blocks of unique frames. The authors used eight different types of dynamic translational  
148 GPs, where the combination between the number of unique frames (maximum 12 frames) and the  
149 update rate (maximum 60 Hz) was manipulated. Participants had to perform a 2IFC task in which  
150 they had to report whether the coherent translational GP was either in the first or second temporal  
151 interval. Their study aimed to test whether the lower discrimination thresholds for dynamic GPs  
152 were associated not only with high update rates, as found previously by Day and Palomares (2014),  
153 but also with a specific number of unique frames composing the GPs. The hypothesis was that if the  
154 perception of dynamic GPs is driven by form information summation, then it should be observed  
155 increased sensitivity of dynamic GPs as the number of unique frames increases. The authors  
156 showed that dynamic GPs with more unique frames are easier to discriminate because of the  
157 temporal summation of local signals. The authors chose to use translational GPs and no other  
158 spatial configurations because Nankoo et al. (2012) showed a more evident difference between  
159 discrimination thresholds for translational static and dynamic GPs than between other  
160 configurations such as spiral, radial, and circular. In other terms, using translational GPs, the  
161 divergence between GPs with a different number of unique frames and temporal frequencies should  
162 be more evident than other GPs configurations. These results confirmed that participants could  
163 better discriminate (i.e., lower coherence thresholds) dynamic translational GPs with twelve frames  
164 and an update rate of 60 Hz than with a lower number of frames, even if the resulting temporal  
165 frequency was the same. However, the authors concluded that motion mechanisms could also  
166 contribute to the better discrimination of dynamic translational GPs.

167 In this study, we examined whether global form signal in dynamic circular and translational  
168 GPs is integrated across frames and whether this facilitates participants' discrimination of dynamic  
169 GPs. Specifically, we aimed at investigating the mechanisms underlying the coding of both static  
170 and dynamic GPs for translational and circular configurations. This was tested by using the method

171 of Nankoo et al. (2015) with the same combination of unique frames and pattern update rates to  
172 assess whether there are overlapping mechanisms between the processing of simple (translational)  
173 and complex (circular) GP configurations. The present study aims to investigate whether  
174 participants' discrimination coherence thresholds for translational and circular GPs rely either on  
175 the number of unique frames that form dynamic GPs or on the pattern update rate independently  
176 from the number of unique frames. If the participants' sensitivity to GPs depends exclusively on the  
177 number of unique frames used, this could indicate summation of multiple form signals across  
178 frames (Nankoo et al., 2015). Therefore, as in Nankoo et al. (2015), we expect a linear decrease in  
179 discrimination thresholds as the number of unique frames increases. In the second case, if  
180 participants' sensitivity depends on the pattern update rate, this could indicate the temporal  
181 integration of local motion signals. We should expect a linear decrease of the discrimination  
182 threshold as the pattern update rate increases regardless of the number of unique frames involved.  
183 Moreover, we expect to observe lower discrimination thresholds for circular GPs than translational  
184 GPs throughout all the conditions, regardless of the number of unique frames and the pattern update  
185 rate. This expectation is based on previous studies (Lee & Lu, 2010, Nankoo et al., 2012; Rampone  
186 & Makin, 2020; Wilson & Wilkinson, 1998), which found that human observers are more sensitive  
187 to complex GPs (e.g., circular and radial patterns) than simple translational GPs.

188

## 189 **2. Method**

### 190 *2.1. Participants*

191 Twenty participants took part in the experiment. This sample size was established a priori using  
192 G\*Power (Faul et al., 2007, 2009; Mayr et al., 2007) to achieve a power > 0.9 with an effect size of  
193 0.25. All participants had normal or corrected to normal vision. In the experiment, viewing was  
194 binocular. All participants took part in two sessions on two different days (i.e., a session with  
195 translational GPs and another session with circular GPs). Participants were thirteen females and  
196 seven males with a mean age of 25 yrs. (SD: 7.33 yrs.). Two of the authors (RD and AP) performed  
197 the experiment; all the other participants were *naïve* to the study's purposes. Participants were  
198 informed about the research's general aim, and they signed a written informed consent prior the  
199 enrollment to the experiment. The experiment was run in agreement with the World Medical  
200 Association Declaration of Helsinki (2013). The study was approved by the Ethics Committee of  
201 the Faculty of Psychology and Educational Sciences of the University of Coimbra.

202

203

204 2.2. *Apparatus*

205 Visual stimuli were displayed on a 23.8-inch Hp Elite E240 monitor with a spatial resolution  
 206 of 1920 x 1080 pixel and a refresh rate of 60 Hz. Each pixel subtended ~1.65 arcmin. All  
 207 participants sat in a dimly light room at a viewing distance of 57 cm from the screen. Visual stimuli  
 208 were presented using Matlab Psychtoolbox-3 (<http://psychtoolbox.org/>) (Brainard, 1997; Kleiner et  
 209 al., 2007; Pelli, 1997).

211 2.3. *Stimuli*

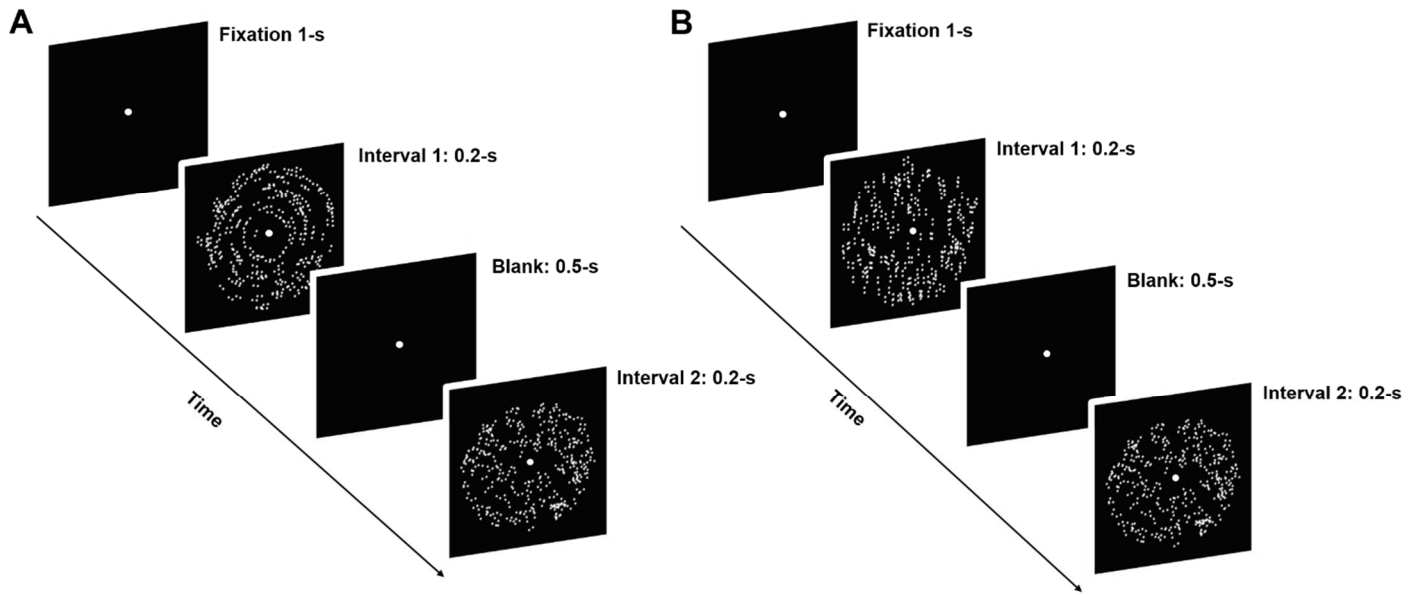
212 The visual stimuli used in the experiment were translational and circular GPs (see Figure 1).  
 213 Both translational and circular GPs were characterized by 2146 white dipoles (density: 6%)  
 214 presented on a black background (Nankoo et al., 2015). The dot separation was 0.25 deg, and each  
 215 dot had a diameter of 0.04 deg. GPs were presented in a circular window within an annulus with a  
 216 maximum radius of 5.35 deg (diameter: 10.7 deg). Static GPs were composed of a single unique  
 217 frame, whereas dynamic GPs were made of multiple independent frames presented in rapid  
 218 succession (each frame had a duration of 0.0167-s). The duration of the stimulus was 0.2-s. The  
 219 sequence and number of unique frames (and relative pattern update rate) composing static and  
 220 dynamic GPs are reported in Table 1 (Nankoo et al., 2015). It should be noted that in condition 1  
 221 (i.e., the same 12 unique frames) the GPs, being presented for 0.2-s, have an update rate of 5 Hz and  
 222 are perceived as static patterns. At the center of the annulus, a white fixation point with a diameter  
 223 of 0.3 deg was always present.

224

Condition	Sequence of Unique Frames	Number of Unique Frames	Pattern Update Rate (Hz)
1	AAAAAAAAAAAA	1	5
2	ABCDEFGHIJKL	12	60
3	AAAAAABBBBBB	2	10
4	AAABBBAAABBB	2	20
5	ABABABABABAB	2	60
6	AAABBBCCDDDD	4	20
7	ABCDABCDABCD	4	60
8	AABBCCDDEEFF	6	30



225  
 226 **Table 1.** Summary of the conditions used in the experiment. Number of unique frames, frame  
 227 sequences and pattern update rates used in the experiment are reported. The letters reported in the  
 228 second column indicate the sequence of unique frames. Each participant performed all the nine  
 229 conditions with the two types of GPs: circular and translational GPs. This scheme is the same as in  
 230 Nankoo et al. (2015).  
 231



232  
 233 **Figure 1.** Representation of the visual stimuli and the procedure used in the experiment. Two  
 234 temporal intervals of 0.2-s with a circular GP (A) or a translational GP (B) were presented after 1-s  
 235 fixation. Panel A and B show respectively a circular and a translational GP with 100% coherence in  
 236 the first temporal interval and a GP with 0% coherence (i.e., noise pattern) in the second temporal  
 237 interval.  
 238

238

### 239 3. Procedure

240 Participants performed two sessions of two hours each and on two different days. The two  
 241 sessions had the same procedure but differed for the type of visual stimulus used, i.e., either  
 242 translational or circular GPs. The order of the two sessions was alternated amongst the participants.  
 243 At the beginning of each session, each participant was instructed about the type of GP presented  
 244 and they performed twenty trials to familiarize with the stimulus and task. During the training  
 245 phase, one interval contained a GP with maximum coherence (100%) and the other interval a GP  
 246 with randomly oriented dipoles (i.e., noise GP – 0% coherence). Each trial started with a fixation  
 247 point of 1-s, followed by two 0.2-s temporal intervals separated by a blank interval of 0.5-s. One of

248 the two intervals always contained a coherent GP (either translational or circular, depending on the  
 249 session) and the other interval a noise GP. The presentation order of the two intervals was  
 250 randomized across trials. Observers performed a 2IFC task and had to report whether the first or  
 251 second interval contained the coherent GP using the key “A” to indicate the first temporal interval  
 252 and the key “L” to indicate the second temporal interval, on a standard Portuguese computer  
 253 keyboard.

254 An Updated Maximum-Likelihood (UML) staircase procedure was used with a 1 up – 3  
 255 down rule to estimate participants’ parameters of the psychometric function (Shen & Richards,  
 256 2012; Shen, Dai, & Richards, 2014). In this case, the threshold corresponds to a coherence level for  
 257 which participants were at 79% correct performance.

258 The UML procedure allows efficient data collection to estimate the parameters of the  
 259 psychometric function using an optimized strategy for stimulus sampling (Shen & Richards, 2012).  
 260 In our implementation of the UML procedure, the Cumulative Gaussian was selected as  
 261 psychometric function and had the following form:

$$263 \quad p(\text{correct}) = \gamma + (1 - \gamma - \lambda) \frac{1}{2} \left[ 1 + \operatorname{erf} \left( \frac{x - \alpha}{\sqrt{2\beta^2}} \right) \right] \quad \text{Eq. 1}$$

264  
 265 where  $\alpha$  is the center of the psychometric function,  $\beta$  is associated with the slope of the  
 266 psychometric function,  $\gamma$  is the proportion correct for chance performance that in our case was fixed  
 267 at 0.5, which set the lower bound of the psychometric function, and  $\lambda$  is the difference between the  
 268 upper asymptote of the function and one, indicating the lapses rate.

269 The initial signal strength, i.e., number of coherently oriented dipoles, was set at 1800  
 270 dipoles, with limits in the interval [100 2000]. The range of the parameter  $\alpha$  (i.e., coherence  
 271 threshold) was in the interval [200 1900], with a prior uniform distribution. The range of the  
 272 parameter  $\beta$  was in the interval [0.05 20] with a prior uniform distribution. The range of the  
 273 parameter  $\lambda$  was in the interval [0 0.1], again with a prior uniform distribution. For each participant,  
 274 the coherence threshold was calculated from the best parameters of the Cumulative Gaussian  
 275 estimated with the UML procedure, finding the coherence corresponding to the 79% correct  
 276 performance from the psychometric function. The slope of the Cumulative Gaussian function,  
 277 calculated at the coherence threshold, can be derived as follows:

$$278 \quad s = \frac{1 - \gamma - \lambda}{\sqrt{2\pi\beta^2}} \quad \text{Eq. 2}$$

280 In both sessions, participants perform all the nine conditions (see Table 1), randomized  
281 among the participants and throughout the sessions. Each condition (and UML staircase) consisted  
282 of 150 trials.

283

## 284 4. Results

### 285 4.1. Discrimination thresholds

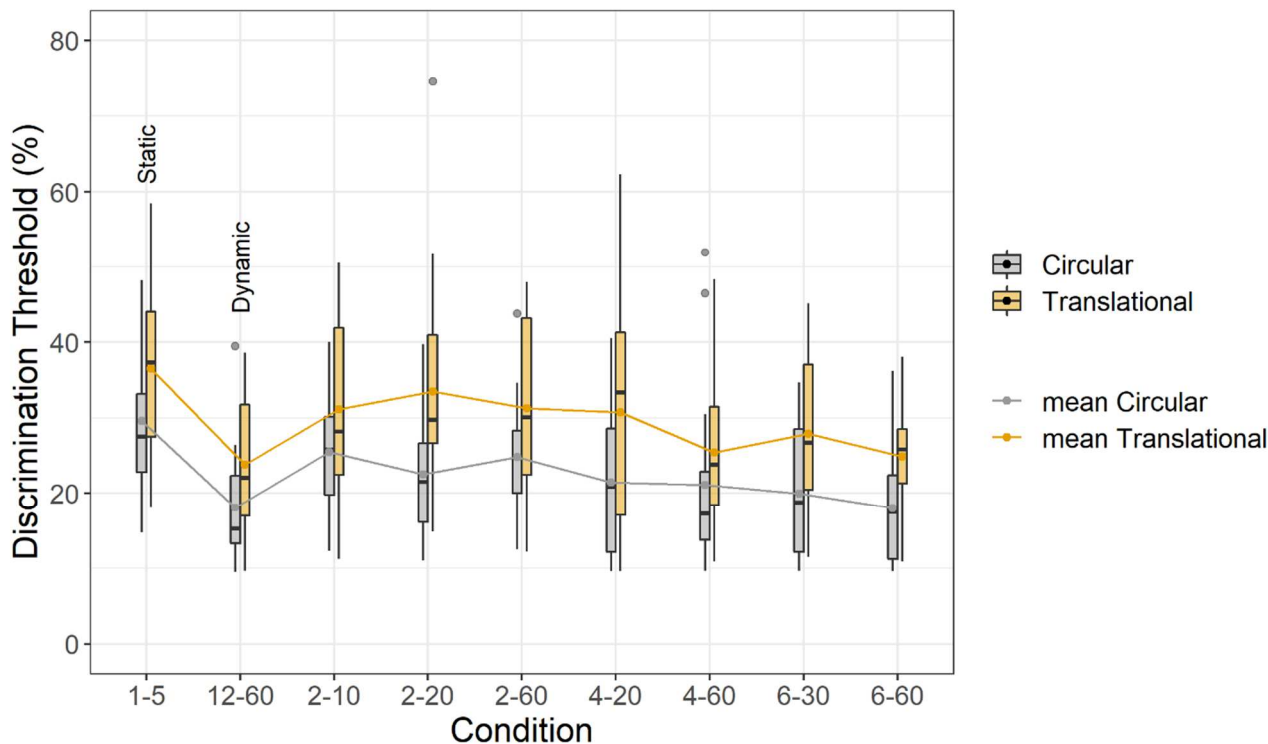
286 Discrimination thresholds for dynamic circular GPs (12 frames; 60 Hz) (mean: 18%, SD:  
287 7.23%) were significantly lower than discrimination thresholds for static circular GPs (1 frame)  
288 (mean: 30%; SD: 9.69%) ( $t_{(19)} = 5.53, p < 0.001$ ; *Cohen's d*<sup>1</sup> = 2.7). The same significant difference  
289 was obtained when comparing dynamic translational GPs (12 frames; 60 Hz) (mean: 24%; SD:  
290 9.25%) with static translational GPs (1 frame) (mean: 37%; SD: 11.36%) ( $t_{(19)} = 6.28, p < 0.001$ ;  
291 *Cohen's d* = 2.7).

292 Figure 2 shows the discrimination thresholds for circular and translational GPs for each  
293 experimental condition (Table 1). A Shapiro-Wilk test found that residuals for both circular and  
294 translational GPs were normally distributed ( $p = 0.5$  and  $p = 0.6$ , for circular and translational GPs,  
295 respectively). A two-way repeated measures ANOVA including as within-subjects factors the GP  
296 type (circular vs. translational) and the temporal condition (i.e., number of unique frames and  
297 pattern update rate) showed a significant effect of the GP type ( $F_{(1,19)} = 15.67, p < 0.001, partial-$   
298  $\eta^2 = 0.45$ ), a significant effect of the temporal condition ( $F_{(8,152)} = 12.67, p < 0.001, partial-\eta^2 = 0.4$ ),  
299 but not a significant interaction between GP type and temporal condition ( $F_{(8,152)} = 1.059, p = 0.3,$   
300  $partial-\eta^2 = 0.05$ ). For GP type, circular GPs had always lower discrimination thresholds than  
301 translational GPs across all the conditions tested. Post hoc *t-test* comparisons corrected with False  
302 Discovery Rate (FDR) with  $\alpha=0.05$  (Benjamini & Hochberg, 1995) between the different  
303 conditions are reported in Table 2.

304

---

<sup>1</sup> The *Cohen's d* was calculated dividing the mean difference of the two conditions (i.e., static and dynamic GPs) for the difference of the standard deviation of the two conditions: *Cohen's d* = (mean2 - mean1)/SD2-SD1.



305

306 **Figure 2.** Boxplots of discrimination thresholds (%) of the two experiments with circular (grey  
 307 bars) and translational (dark yellow bars) GPs. The x-axis reports the nine conditions used in the  
 308 experiments: number of unique frames and pattern update rate of the GPs. For each boxplot, the  
 309 horizontal black line indicates the median, the lower and upper hinges correspond to the first and  
 310 third quartiles (i.e., the 25<sup>th</sup> and 75<sup>th</sup> percentiles). Instead, the dot within each boxplot represents the  
 311 mean discrimination threshold. The upper whisker extends from the hinge to the largest value no  
 312 further than  $1.5 * IQR$  of the hinge (where IQR is the inter-quartile range or distance between the  
 313 first and third quartiles). The lower whisker extends from the hinge to the smallest value at most  $1.5$   
 314  $* IQR$  of the hinge.

315

Circular GPs									
Conditions	1-5	12-60	2-10	2-20	2-60	4-20	4-60	6-30	6-60
12-60	0.0002***								
2-10	0.1037	0.0014***							
2-20	0.0024**	0.0693	0.0649						
2-60	0.0344**	0.0020**	0.6336	0.1466					
4-20	0.0001***	0.1477	0.0267*	0.4164	0.0826				
4-60	0.0014***	0.3344	0.0667	0.3344	0.1124	0.7729			
6-30	0.0002***	0.2053	0.0003***	0.1281	0.0031**	0.3344	0.6336		
6-60	0.0001***	0.9603	0.0002***	0.0015***	0.0006***	0.0201*	0.0482*	0.2743	

316 **Table 2.** Summary of the FDR adjusted  $p$ -values for multiple post hoc comparisons between the  
 317 different temporal conditions of the experiment (the first digit indicates the number of unique  
 318 frames in the sequence, whereas the second digit the pattern update rate). The asterisks indicate  
 319 significant comparisons ( $*p < 0.05$ ,  $**p < 0.01$ ,  $***p < 0.001$ ).

320

321 For translational GPs, FDR post hoc comparisons are reported in Table 3.

322

Translational GPs								
Conditions	1-5	12-60	2-10	2-20	2-60	4-20	4-60	6-30
12-60	0.0002***							
2-10	0.1532	0.0470*						
2-20	0.4615	0.0141**	0.0644					
2-60	0.0223*	0.0200*	10.000	0.4998				
4-20	0.1265	0.0470*	10.000	0.6044	0.9728			
4-60	0.0034**	0.6044	0.0200*	0.0367*	0.0647	0.1982		
6-30	0.0034**	0.0647	0.2051	0.1194	0.1532	0.3894	0.4344	
6-60	0.0006***	0.7482	0.0373*	0.0223*	0.0200*	0.0470*	0.9675	0.1177

323

324 **Table 3.** Summary of the FDR adjusted  $p$ -values for multiple post-hoc comparisons between the  
 325 different conditions. The asterisks indicate the significant comparisons (significance levels:  $*p <$   
 326  $0.05$ ,  $**p < 0.01$ ,  $***p < 0.001$ ).

327

328 To assess the relationship between (i) discrimination thresholds and number of unique  
 329 frames and (ii) the relationship between discrimination thresholds and GPs' update rate, data were  
 330 fitted with three different functions: a power law function, an exponential function, and a linear  
 331 function. The aim was to test which model better described the data and whether there were  
 332 differences in model's parameters between circular and translational GPs (see the Supplementary  
 333 Material for the fitting procedure and model selection). We found that for both translational and  
 334 circular GP, discrimination thresholds were best modelled by a power law function of the form:

335

$$y = ax^{-b} \quad \text{Eq. 3}$$

337

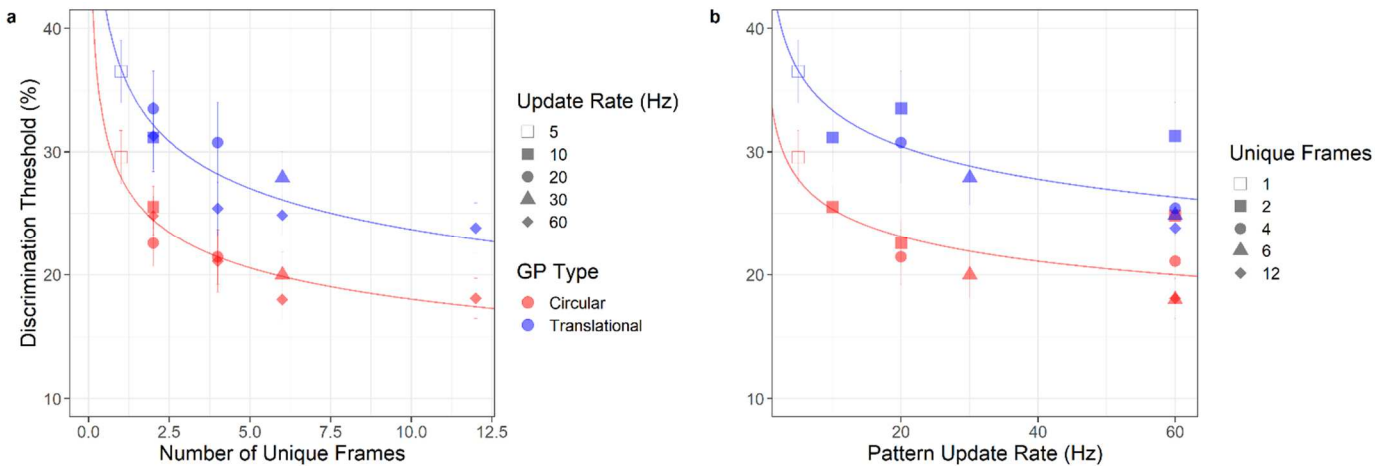
338 where  $a$  is the scale parameter and  $b$  is the power law exponent.

339 Once selected the best fitting model (i.e., the power law function), we created and fitted a  
 340 lattice of power law functions to discrimination thresholds. The lattice of models ranged from a  
 341 fully saturated model with four parameters (one  $a$  and  $b$  parameter per GP type) to a maximally  
 342 restricted model with only two parameters ( $a$  and  $b$ ). Between the fully saturated model and the  
 343 maximally restricted model, a lattice of models with three parameters were fitted (see the  
 344 Supplementary Material for more details). We found that a restricted model consisting of different  
 345 parameters  $a$  across the two GP types, but the same power law exponent ( $b$ ) was the best fitting  
 346 model. The selected model had the following form:

$$f1(x) = a1x^{-b} \quad \text{Eq. 4}$$

$$f2(x) = a2x^{-b}$$

347  
 348  
 349  
 350  
 351 where  $f1(x)$  indicates the function fitted to the circular GPs and  $f2(x)$  indicates the function fitted to  
 352 translational GPs. The model consists of different parameters  $a$  (i.e.,  $a1$  and  $a2$ ) across the two GP  
 353 types, but the same power law exponent  $b$  (Figure 3). For the number of unique frames, restricted  
 354 model 2 had the following estimated parameters:  $a1 = 27.94$  (SE: 0.84),  $a2 = 36.73$  (SE: 0.97),  $b =$   
 355  $0.191$  (SE: 0.019) ( $quasi-R^2 = 0.92$ ), whereas for the pattern update rate restricted model 2 had the  
 356 following parameters:  $a1 = 34.35$  (SE: 2.88),  $a2 = 45.24$  (SE: 3.63),  $b = 0.132$  (SE: 0.024) ( $quasi-R^2$   
 357  $= 0.79$ ).

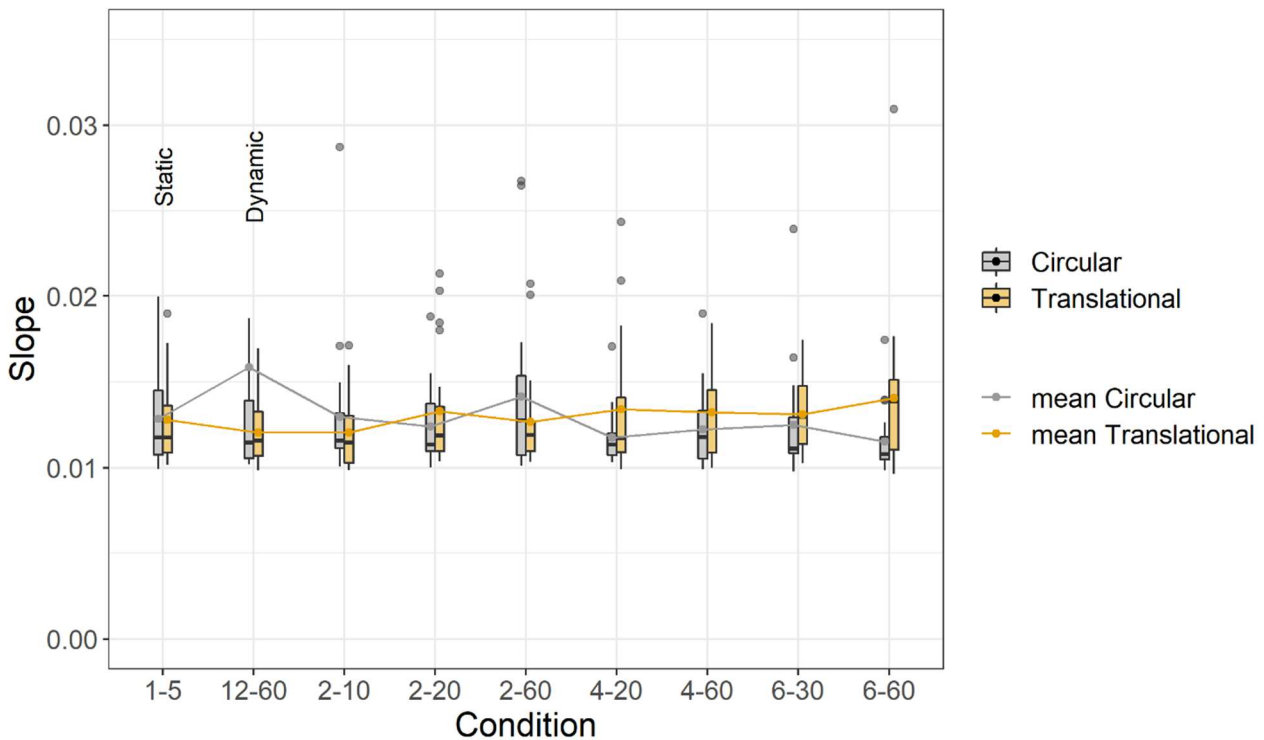


358  
 359 **Figure 3.** (a) Discrimination thresholds as a function of the number of unique frames for circular  
 360 (red symbols) and translational GPs (blue symbols). (b) Discrimination thresholds as a function of  
 361 the pattern update rate for circular and translational GPs. The curves represent the best fitting model  
 362 to the data (i.e., Restricted Model 2 [Eq. 4], see the Supplementary Material). Error bars  $\pm$ SEM.

363  
 364

365 4.2. Slopes

366 The slopes give information about the reliability of the estimated discrimination thresholds.  
 367 Low values of the slopes are related to a smooth psychometric function, indicating higher  
 368 uncertainty in discrimination of the visual stimuli. A two-way repeated measures ANOVA on the  
 369 slopes including as within subjects factors the GP type and the temporal condition did not report  
 370 any significant effect or interaction (GP type:  $F_{(1,19)} = 0.008$ ,  $p = 0.9$ ,  $partial-\eta^2 = 0.001$ ; temporal  
 371 condition:  $F_{(8,152)} = 0.39$ ,  $p = 0.9$ ,  $partial-\eta^2 = 0.02$ ; interaction between GP type and temporal  
 372 condition:  $F_{(8,152)} = 1.56$ ,  $p = 0.1$ ,  $partial-\eta^2 = 0.08$ ) (Figure 4).



373  
 374 **Figure 4.** Boxplots of the slopes. The x-axis reports the nine conditions used during the experiment:  
 375 number of unique frames and pattern update rate of the GPs. For each boxplot, the horizontal black  
 376 line indicates the median, the lower and upper hinges correspond to the first and third quartiles (i.e.,  
 377 the 25<sup>th</sup> and 75<sup>th</sup> percentiles).

378  
 379 **5. Discussion**

380 The present study investigated how the human visual system discriminates simple and  
 381 complex apparent and non-directional motion generated by translational and circular GPs. We  
 382 measured discrimination thresholds and slopes for circular and translational GPs by varying the  
 383 number of unique frames composing the pattern and the relative update rates. Our results show that  
 384 (i) circular GPs are more easily discriminated than translational GPs; (ii) translational and circular  
 385 GPs are influenced equally by both the number of unique frames and the pattern update rate; it is

386 not only the pattern update rate but also the number of unique frames that influences the observer's  
387 perception of GPs; (iii) dynamic translational and circular GPs are perceived better than the static  
388 GPs; (iv) there are no differences between slopes across all the temporal conditions tested,  
389 indicating that only the coherence threshold was affected by the temporal manipulations (in terms  
390 of number of unique frames and pattern update rate) but not the overall sensitivity of the system.

391 The evidence that the human visual system shows higher sensitivity to circular GPs than  
392 translational GPs is in line with previous psychophysical works (Nankoo et al., 2012; Rampone &  
393 Makin, 2020; Wilson & Wilkinson, 1998). For example, Rampone and Makin (2020) performed a  
394 study exploring the human brain responses for static translational, circular, and radial GPs by using  
395 electroencephalogram (EEG) and event-related potentials (ERPs). The authors examined the trend  
396 of the sustained posterior negativity (SPN), an ERP component associated with the perceptual  
397 goodness of specific geometric configurations. Participants showed a similar SPN for circular and  
398 radial static GPs with respect to translational GPs that were, in turn, the most difficult to detect.  
399 Interestingly, other studies found similar results with directional motion (Freeman & Harris, 1992;  
400 Lee & Lu, 2010). In particular, Lee and Lu (2010) compared participants' coherence thresholds for  
401 circular, radial and translational motion. The results showed greater sensitivity to complex motion  
402 than to translational motion and named this phenomenon as "*the complexity advantage*". This result  
403 was in line with a previous study by Freeman and Harris (1992), that found that circular and radial  
404 RDKs were easier to detect than translational RDKs. However, other studies with RDKs showed  
405 contrasting results (Ahlstrom & Borjesson, 1996; Bertone & Faubert, 2003). For example, Bertone  
406 and Faubert (2003) using second-order motion (i.e., when the moving contour is defined by  
407 qualities that does not result in an increase in luminance or motion energy in the Fourier spectrum  
408 of the stimulus [e.g., contrast, texture, flicker, etc.]; Cavanagh & Mather, 1989; Chubb & Sperling,  
409 1988), showed that participants were more sensitive to translational RDKs than circular and radial  
410 RDKs. On the other hand, other studies did not find any difference in detection thresholds for  
411 translational, radial, and circular RDKs (Blake & Aiba, 1998; Morrone et al., 1995). Therefore,  
412 more psychophysical studies are necessary to further investigate how the human visual system  
413 detects and discriminates simple and complex motion.

414 In the present study, we also assessed the relationship between participants' discrimination  
415 thresholds and the two independent variables manipulated: the number of unique frames and pattern  
416 update rate. We showed that discrimination thresholds decrement for both GP types is better  
417 described by a power law function with different scale parameters ( $a$ ) but same power law exponent  
418 ( $b$ ). Therefore, the best fitting model describing our data supports the presence of a power  
419 relationship between discrimination thresholds and number of unique frames and between



420 discrimination thresholds and pattern update rate, and not a linear relationship as assumed by  
421 Nankoo et al. (2015), though in their Figure 3 (page 33) the relationship between detection  
422 thresholds and number of unique frames and between detection thresholds and pattern update rates  
423 is likely to be either power or exponential. Our results suggest that the form signal contained in  
424 each unique frame and the pattern update rate equally contribute to shape the perception of  
425 translational and circular GPs. Additionally, the best fitting model shows that discrimination  
426 thresholds start at a lower value for circular GPs than for translational GPs (see Figure 3 and the  
427 Supplementary Material), but the rate at which the power law function reaches the lower  
428 discrimination threshold is the same for the two GP types. In general, observers better discriminated  
429 circular GPs than translational GPs, though coherence thresholds decreased at the same rate for both  
430 GP types as increasing the number of unique frames and pattern update rate.

431 Furthermore, looking at Figure 3, it could be observed that it is not only the pattern update  
432 rate important for the perception of GPs, as previously stated by Day and Palomares (2014), but  
433 also the number of unique frames that forms the pattern plays an important role. In particular, we  
434 showed that discrimination thresholds in correspondence to the condition with two unique frames  
435 do not vary across the different update rates (i.e., 10, 20, and 60 Hz – see Table 1), for both GP  
436 types. Therefore, it seems that discrimination thresholds do not vary with the pattern update rate if  
437 the same spatial information is present in the visual stimulus. Moreover, looking at the four  
438 conditions with a pattern update rate of 60 Hz (i.e., with 2, 4, 6, and 12 unique frames – Table 1),  
439 the lower detection thresholds were estimated with the highest number of unique frames used (i.e.,  
440 6 and 12 unique frames) in both GP types. These results might reflect a short integration window  
441 between 100 and 200 ms, perhaps comprising the time over which form information is integrated.  
442 In general, this may suggest the existence of mechanisms of spatial/form integration in dynamic  
443 translational and circular GPs that, along with the pattern update rate, play a fundamental role in the  
444 perception of this class of visual textures (Day & Palomares, 2014; Nankoo et al., 2015; Ross et al.,  
445 2000).

446 Finally, our study shows also higher discrimination thresholds for static circular and  
447 translational GPs (1 unique frame, 5 Hz) than dynamic GPs, regardless of the temporal condition.  
448 Nankoo et al. (2015) argued that this is due to the spatial summation of form signals from all the  
449 independent frames composing the dynamic GP. As previously reported, we found that lower  
450 discrimination thresholds were obtained with the highest update rate used (i.e., 60 Hz) and with the  
451 highest number of unique frames (i.e., 12) that formed the dynamic GPs. Therefore, we argue that  
452 both translational and circular dynamic GPs are processed according to a spatial and temporal  
453 summation process. Besides, Burr (1980) argued that the temporal summation in a dynamic visual

454 stimulus leads to significant signal improvements to noise levels. Day and Palomares (2014) found  
455 an inverse relationship between the pattern update rate and the participants' detection thresholds; as  
456 the pattern update rate increased, observers' detection threshold decreased. The authors showed that  
457 the visual system integrates both temporal and orientation signals to improve the detection of  
458 ambiguous motion, such as the apparent and non-directional motion generated by dynamic GPs. A  
459 possible explanation of this phenomenon could be attributed to the formation of *motion streaks*  
460 (Geisler, 1999). Over time, summation of responses to a moving visual object, when it is moving  
461 with adequate speed, produces "*speed lines*" or "*motion streaks*" that extend backwards across the  
462 retina from the object and display the character of the movement (Burr, 1980; Burr & Ross, 2002),  
463 due to temporal integration (Geisler, 1999). Motion streaks aligned to the direction of motion aid  
464 the observer to identify a trajectory of a moving object (Apthorp, Schwarzkopf, Kaul, Bahrami,  
465 Alais, & Rees, 2013; Geisler, 1999) or the axis of apparent and non-directional motion in the case  
466 of dynamic translational GPs (Ross et al., 2000). This phenomenon indicates that the  
467 orientation/form signal contributes to the perception of apparent motion. In line with this evidence,  
468 the current study shows that both the orientation/form signals and the temporal signals (i.e.,  
469 generated by the update rate) are integrated to shape the perception of the apparent and non-  
470 directional motion in both GP types.

471 In summary, our results indicate that perception of apparent and non-directional motion  
472 evoked by dynamic complex and simple GPs is strongly and equally influenced by temporal and  
473 form summation mechanisms in which dipoles' orientation information is summed across frames.  
474 The human visual system integrates form and temporal information to shape the perception of non-  
475 coherent motion in dynamic GPs. Additionally, the difference in the discrimination thresholds  
476 between translational and circular GPs further confirms that different form and motion integration  
477 processes subserve the perception of complex and simple global shapes.

478

## 479 6. Conclusion

480 Apparent and non-directional motion generated by dynamic translational and circular GPs  
481 seems to be processed by a wide range of low- and high-level visual areas (Krekelberg et al., 2005;  
482 Ostwald et al., 2008). We showed that form and motion processing in dynamic circular and  
483 translational GPs interact. We partially replicated the study of Nankoo et al. (2015) showing that  
484 dynamic GPs are easier to discriminate than static configurations. This occurs not only because of  
485 the spatial summation of the form signals from unique frames but also because of temporal  
486 summation. Moreover, we extended the findings of Nankoo et al. (2015) by assessing the role of the  
487 number of unique frames and the pattern update rate in circular GPs. Interestingly, we found that

488 both these variables play the same role in translational and circular GPs. We conclude that it is not  
489 only the pattern update rate that aids the discrimination of apparent and non-directional motion  
490 from translational and circular GPs (Day & Palomares, 2014), but it also depends on the amount of  
491 form signals that are summed by the visual system over the frames.

492

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503

### 504 **Conflict of interest**

505 The authors declare no competing financial interests.

506

### 507 **Author contribution**

508 **Rita Donato, Andrea Pavan:** Conceptualization and Methodology. **Andrea Pavan:** Software.  
509 **Rita Donato:** Data collection. **Rita Donato, Andrea Pavan:** Data curation. **Rita Donato, Andrea**  
510 **Pavan:** Data analysis. **Rita Donato, Andrea Pavan:** Writing, Original draft preparation. **Andrea**  
511 **Pavan, Gianluca Campana:** Supervision. **Rita Donato, Andrea Pavan, Gianluca**  
512 **Campana:** Writing- Reviewing and Editing. **Massimo Nucci, Jorge Almeida:** Reviewing and  
513 Editing.

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