

Empathy modulates the temporal structure of social attention

Article

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Hedger, N. ORCID: <https://orcid.org/0000-0002-2733-1913>,
Haffey, A., McSorley, E. ORCID: <https://orcid.org/0000-0002-2054-879X> and Chakrabarti, B. ORCID: <https://orcid.org/0000-0002-6649-7895> (2018) Empathy modulates the temporal structure of social attention. *Proceedings of the Royal Society B: Biological Sciences*, 285 (1893). 20181716. ISSN 0962-8452 doi: 10.1098/rspb.2018.1716 Available at <https://centaur.reading.ac.uk/81241/>

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1 Empathy Modulates the Temporal Structure of Social Attention

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Nicholas Hedger ^a, Anthony Haffey ^a, Eugene McSorley ^a Bhisudev Chakrabarti ^a

Psychology, University of Reading, Reading, RG6 6AL, UK

Corresponding author: Bhisudev Chakrabarti.

Email: b.chakrabarti@reading.ac.uk

Phone: +44 118 378 5551

Address: School of Psychology and CLS, Reading, Reading, RG6 6AL, UK.

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Author Contributions.

30

31 *NH* carried out the statistical analysis and wrote the initial draft of the paper. *BC, EM, and*
32 *AH* conceived of the study design, coordinated data collection and provided modifications to
33 the initial manuscript draft. All authors declare that they have no conflicting or competing
34 interests in relation to this article.

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Abstract

Individuals with low empathy often show reduced attention towards social stimuli. A limitation of this literature is the lack of empirical work that has explicitly characterised how this relationship manifests itself over time. We investigate this issue by analysing data from two large eye-tracking datasets (total $N = 176$). Via growth-curve analysis, we demonstrate that self-reported empathy (as measured by the empathy quotient - EQ) predicts the temporal evolution of gaze behavior under conditions where social and non-social stimuli compete for attention. In both datasets, we found that EQ not only predicted a global increase in social attention, but predicted a different temporal profile of social attention. Specifically, we detected a reliable effect of empathy on gaze towards social images after prolonged viewing. An analysis of switch latencies revealed that low EQ observers switched gaze away from an initially fixated social image more frequently and at earlier latencies than high EQ observers. Our analyses demonstrate that modeling these temporal components of gaze signals may reveal useful behavioral phenotypes. The explanatory power of this approach may provide enhanced biomarkers for conditions marked by deficits in empathy related processes.

Keywords: Eye-tracking; empathy, social attention

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67 To enable successful interactions with the environment, organisms must
68 preferentially attend to socially significant stimuli. Failure to engage with conspecifics can
69 result in exclusion and status loss, which are significant and recurrent fitness threats [1].
70 Moreover, attending to social stimuli allows the accumulation of strategically beneficial
71 information such as the physical strength of a potential rival, the social standing of a
72 potential ally, or the genetic fitness of a potential mate [2]. In humans, such 'social attention'
73 is also crucial for the development of communicative skills such as language acquisition and
74 emotion recognition [3].

75 Empathy has been defined as the drive to identify with another person's emotions
76 and thoughts, and to respond to these with an appropriate emotion [4]. In order to identify
77 with another's emotions and respond appropriately, it is essential to attend to socially
78 relevant cues such as bodily postures and facial expressions - which provide important
79 information for decoding the emotional states of other people [5,6]. Social attention can
80 therefore be conceptualised as an essential precursor to an empathic response. Support for
81 this view has come primarily from case-control eye-tracking studies, which have
82 demonstrated that individuals with deficits in some empathy related processes also show
83 deficits in social attention. For instance, a recent meta-analysis revealed robust evidence
84 that Autism Spectrum Conditions (ASC) are associated with a reduction in social attention
85 that generalises across a wide range of tasks and stimulus conditions [7]. Influential case-
86 control eye-tracking studies have indicated that individuals with ASC exhibit reduced
87 attention to biological relative to non-biological motion patterns [8] and exhibit a preference
88 to direct gaze towards geometric patterns when they compete with videos of social
89 interactions [9]. However, other studies have called into question whether social attention
90 differences are meaningfully related to the aetiology and maintenance of ASC [10,11]. The
91 heterogeneity in reported outcomes is possibly due to the heterogeneous nature ASC and
92 the small sample sizes resulting from the practical issues associated with case-control
93 designs. In this context, it is surprising that there is almost no literature that has attempted to

94 model *individual*, rather than *group* variation in social attention in the neurotypical
95 population. One recent study has demonstrated that trait empathy is associated with a gaze
96 bias towards social rewards in the neurotypical population [12]. Although this observation
97 indicates that social attention is generally reduced in individuals with low empathy, the
98 *features* of gaze behavior underlying this reduction remain fundamentally unclear.

99 The output of a typical eye-tracking experiment is a continuous stream of spatial
100 coordinates that define the location of an observer's gaze over time. To describe individual/
101 group differences in social attention, this time series is typically collapsed into the total gaze
102 duration towards areas of interest (AOI's) containing social and non-social stimuli [7]. Whilst
103 total gaze duration is an intuitive and easily interpretable metric, it necessarily involves the
104 removal of informative components of the data contained within the temporal domain. Such
105 an approach may therefore fail in describing more subtle differences between individuals
106 that describe the dynamic nature of social attention. Although some previous studies of
107 social attention have considered the temporal origin of group differences via divergence
108 analyses [13-15] none have provided or tested a quantitative model of the entire time series.
109 To our knowledge, no existing study has provided an explicit model of the temporal structure
110 of social attention and tested predictions about individual-level social gaze behavior over
111 time.

112 The motivation for investigating individual differences in the temporal structure of
113 social attention is not purely data driven. At the theoretical level, prioritised perception of
114 socially relevant signals is one of the most important functions of the visual system. As such,
115 there is a major explanatory burden associated with identifying the features of gaze behavior
116 underlying individual variation in this phenomenon. Neurocognitive theories propose that
117 social attention is mediated by neural circuits that transduce sensory information about
118 conspecifics and translate that information into value signals that bias the spatial allocation
119 of gaze over time [16]. In order to more fully appreciate what drives humans to attend to
120 social aspects of the world, one must investigate the individual characteristics that influence
121 this inherently dynamic process. By extension, this research effort may have the corollary of

122 informing explanatory models of disordered social attention. Moreover, influential models
123 propose that attention involves at least two distinct components of initial 'orienting' to and
124 subsequent 'maintaining' of engagement with stimuli [17]. In global eye-tracking metrics,
125 these two processes are conflated - total gaze duration towards social stimuli could reflect
126 some combination of both the orienting and maintaining mechanisms. Delineating these
127 mechanisms requires explicitly modeling the temporal components of the gaze signal. In
128 general, we may expect empathy to primarily influence gaze behavior some time after
129 stimulus presentation because arriving at an empathic response may require sampling many
130 relevant cues from a scene. We may need to attend to multiple subjects in the scene,
131 determine their event roles, recognise their facial expressions/ bodily postures and integrate
132 this information over time before an empathic response is triggered. This idea is consistent
133 with the recent observation that although empathy is predictive of gaze bias towards social
134 images after prolonged viewing, it does not predict the initial saccadic deviation towards
135 social images in a 'global effect' paradigm [12].

136 In the context of the preceding discussion, there is a clear lack of empirical work that
137 has attempted to model the temporal structure of social attention and its relationship with
138 individual social trait characteristics such as empathy. In this study, our goals were to i)
139 characterise the extent of gaze bias towards social stimuli in a large sample of observers ii)
140 model the time course of this social bias iii) determine how empathy modulates the time
141 course of the social bias. We report data from two large eye tracking datasets, with a
142 combined total of 176 observers.

143 **Dataset 1**

144 **Method**

145 **Participants**

146 Ninety nine participants (58 females, *M* age= 23, *SD* age = 5) were recruited from in
147 and around the University of Reading. Ethical approval for the study was obtained from the
148 Research Ethics Committee of the University of Reading (Ethics ID: 2012/070/BC) and all
149 participants provided informed consent. All participants had normal or corrected to normal

150 vision. All participants except one female completed the Empathy Quotient (EQ) [16] a
151 reliable, behaviorally validated measure of trait empathy. The mean EQ score was 44.21
152 (SD = 11.27), and the scores ranged from 25-73. This distribution of scores closely
153 resembles that previously observed in large-scale surveys of the neurotypical population
154 (e.g. [19]: $N = 190$, $M = 44.5$, $SD = 10.7$).

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156 **Stimuli**

157 Forty pairs of social and nonsocial reward images were taken from the International
158 Affective Picture System (18 pairs [20]) and downloaded from publicly available creative
159 common licensed images databases such as Flickr (22 pairs). All images were the same as
160 used in [10], in which social reward images included one or more humans (e.g. happy
161 individuals) while nonsocial reward images included rewarding nonsocial content (e.g. food,
162 scenery and money - see Supplementary Material S1). All stimuli in the experiment
163 subtended 15.4 x 9.15 degrees of visual angle (DVA), and pairs were separated by 5.29
164 DVA (Fig 1 b).

165 To reduce the influence of extraneous sensory and affective differences between
166 image pairs, all stimulus pairs were matched as closely as possible in terms of low level
167 properties (e.g. luminance, contrast, saliency) as well as perceived valence and arousal -
168 see Supplementary Material S1. In addition, to further characterize the influence of low-level
169 confounds, we presented two *stimulus types*. All image pairs were manipulated via randomly
170 rearranging 10 x 10 pixel grids to create a set of '*scrambled*' images in addition to the *intact*
171 images. The logic of this manipulation is that if simple low-level variability between image
172 pairs drives a gaze bias towards social images, we would expect to find a social bias of
173 similar magnitude for both the intact and scrambled stimulus types. By contrast, if social bias
174 is genuinely driven by the semantic content of the images, we would expect social bias to be
175 substantially reduced for scrambled stimuli.

176 **Procedure**

177 Observers were seated 50 cm in front of a Tobii T60 eye-tracker with an inbuilt 1280

178 x 1024 pixel resolution monitor (60hz refresh rate) and sampling rate of 60Hz (Figure 1a).
179 Stimuli were presented using E-Prime 2.0 (Psychology Software Tools, PA, USA [21])
180 Following a 5-point calibration, participants completed the freeviewing task: Observers were
181 informed that they would be presented with pairs of images side by side for 3 seconds, and
182 that they were free to look wherever they liked during this period. Figure 1b depicts the trial
183 sequence: observers were presented with a fixation cross for 500 ms, followed by a pair of
184 the social and nonsocial stimuli for 3000 ms. To maintain engagement with the task, the
185 color of the fixation cross changed from black to blue on 10% of trials. The participant was
186 asked to report these changes via button press as rapidly as possible. Observers completed
187 80 trials in total (40 image pairs, 2 stimulus types).

188 **Results**

189 **Aggregated Social Bias**

190 Data reduction was performed via the 'eyetrackingR' package, implemented in the R
191 programming language [22] The display coordinates occupied by the social and nonsocial
192 images on each trial were defined as areas of interest (AOIs). We first analysed the data by
193 aggregating across the time dimension. To this end, we reduced the raw gaze data for each
194 participant into the proportion trial time that gaze was directed into the social AOI and
195 nonsocial AOI. This data was submitted to a general linear model with AOI (social,
196 nonsocial) and stimulus type (intact, scrambled) as fixed effects. Reported significance tests
197 of model coefficients were conducted via likelihood ratio tests of nested models containing
198 the coefficients versus those without them. There was a main effect of AOI, indicating gaze
199 bias towards social images $\chi^2(1) = 104.02, p < .001$. Moreover, the predicted interaction
200 between AOI and stimulus type was detected $\chi^2(1) = 18.92, p < .001$ (Figure 1c). The bias
201 for social images was larger in the intact condition ($\beta = 0.12$) than scrambled condition ($\beta =$
202 0.05). Adding EQ to the model revealed a 3 way interaction between AOI, stimulus type and
203 EQ $\chi^2(1) = 5.90, p = .020$. Higher EQ was associated with a larger social bias for intact
204 stimuli than scrambled stimuli (Figure 1d).

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INSERT FIGURE 1 HERE

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Time-course of Social Bias.

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Having analysed the aggregated data expressed as total gaze duration, we next aimed to estimate a parsimonious model that described the time course of social bias across participants. For each observer, we first removed trials for which gaze failed to record for more than 60% of a trial (16% of the data). Next, we reduced each observer's gaze data into the proportion of gaze within the social and non-social AOI in each 100ms time bin from the start to end of the trial. We then removed data from the first 100 ms time bin, since it contained 3 SDs less than the mean number valid samples captured within all time bins. No association was detected between EQ and the number of remaining data points when this cleaning strategy was applied $r(96) = -.019, p = .851$.

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Figure 2a depicts the time course of gaze proportion into the social AOI for intact stimuli. This gaze bias towards social images is not time invariant (Figure 2a), nor is its time course well described by a linear function (Figure 2b). The global pattern is an initial bias towards the social AOI that peaks within the first 500 ms, followed by a nonlinear decline and a partial recovery towards the end of the trial. To model these nonlinear components of the time course, we proceeded via forward selection and tested the performance of models that included higher-order time regressors [23]. To protect against overfitting, we tested the generalisation performance of each model, using standard leave one out (LOO) cross-validation procedures (see Supplementary Material S2, S3). Once linear and quadratic time regressors were added, the addition of higher order terms failed to reduce residuals or improve LOO performance, suggesting that more complex models were prone to overfitting. Therefore, a model with AOI and linear and quadratic time regressors as fixed effects (AIC = -6365.5) was retained as our global model of the time-course of the social bias (Figure 2c).

231

Effect of Empathy on Time Course of Social Bias

232 Having modelled the time course of the social bias pooled across participants, we
233 next attempted to model variation at the individual level. We first tested whether empathy
234 modulates the time-course of the social bias by defining EQ as a predictor of proportion of
235 gaze in the social AOI within each 100 ms time bin. An effect of EQ as a predictor of gaze
236 into the social AOI was detected within 3 ‘clusters’ of contiguous time bins (Figure 2d, see
237 Supplementary Material S4 for a rationale for defining clusters). These were located *i*) at
238 100-900 ms *ii*) at 1500-1600 ms *iii*) at 1800- 2900 ms. Given the multiple tests associated
239 with this analysis, our type 1 error rate may have reached unacceptable levels. Therefore, to
240 protect against false positives, we performed a bootstrapped cluster-based permutation
241 analysis (Supplementary Material S4) akin to that typically applied to electroencephalogram
242 data [24]. After this correction was applied, there was no detectable effect in the second
243 cluster ($p = .316$), whereas the chances of obtaining the summed statistics observed in the
244 first and last cluster under the null hypothesis were estimated to be at $p = .003$ and $p = .002$
245 respectively.

246 With this temporal influence of empathy established, we next proceeded to test
247 models that added EQ as a fixed effect to our initial global model of the time-course
248 (Supplementary Material S5). We first specified a *reduced interactive model*, which
249 constrained EQ to interact only with AOI but not the time regressors. This led to improved
250 model fit $\chi^2(2) = 337.47$, $p < .001$, consistent with the previously observed generalised
251 increase in social bias associated with high EQ . Next we specified a *fully interactive model*,
252 which removed this constraint and allowed EQ to additionally interact with the time
253 regressors. This further improved on the reduced interactive model $\chi^2(4) = 72.70$, $p < .001$.
254 To aid interpretation of this model, its predictions are plotted with the empirical data for 5
255 observers (Figure 2e), whose EQ is ordered from left to right (low to high). The model
256 predicts that EQ is associated with a generalised increase in gaze bias towards the social
257 AOI (i.e. the vertical offset between the blue and green lines), but that this effect is
258 particularly pronounced at the start and end of the trial. Given the complexity of this fully

259 interactive model, we again protected against overfitting via another LOO analysis, which
260 confirmed that this model had the superior performance (Supplementary Material S5).

261 In good agreement with the results of our cluster-based analysis, this confirms that
262 EQ is not only associated with a generalised increase in social bias, but also with a different
263 temporal profile of social bias. Inspection of figure 2e reveals that EQ predicts an initial
264 increase in social attention, but also a more sustained component that maintains social
265 attention at the later portions of the trial.

266

267 ***INSERT FIGURE 2 HERE***

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269 One plausible mechanism for this sustained component is that, after being initially
270 fixated, social images hold attention for longer durations in high empathy individuals than
271 low empathy individuals. To test this possibility, we split trials according to the AOI that was
272 initially fixated and analysed the latency at which observers switched their gaze to the
273 alternate AOI. We reasoned that if empathy was associated with sustained attention on
274 social images, this would be manifested in an interactive effect of EQ and initial AOI on gaze
275 switch latency. Figure 3a depicts the proportion of observers who switched AOI as a
276 function of the initial AOI, EQ (median split for visualisation) and time. Inspection of this
277 figure reveals that low EQ individuals switched from the social AOI more frequently and at
278 earlier latencies than high EQ individuals. The predicted interaction between EQ and initial
279 AOI on switch latency was detected $\chi^2(1) = 4.56, p = .030$. Higher EQ was associated with
280 later switching from the social AOI relative to the nonsocial AOI (Figure 3b).

281

282 ***INSERT FIGURE 3 HERE***

283

284 **Dataset 2**

285 Our analyses of the first dataset indicate a robust effect of empathy on the time
286 course of social attention. To further validate our initial findings, we next tested their
287 generalisation performance via a re-analysis of an existing, independent dataset [12].
288

289 **Method**

290 **Participants**

291 77 participants (42 females; $M = 21$ years, $SD = 3$ years) drawn from in and around
292 the University of Reading campus completed the FV task. All participants had normal or
293 corrected to normal vision. 68 (38 female) participants completed the online EQ
294 questionnaire. The study was approved by the University of Reading Research Ethics
295 Committee (Ethics ID: 2010/86/BC).

296 **Stimuli**

297 The images and image pairings were the same as those described for Dataset 1.

298 **Procedure**

299 The only procedural differences from those described in Dataset 1 were as follows.
300 Participants were seated at 100 cm from a 1600 x 1200 pixel resolution colour monitor (75hz
301 refresh rate). Eye movements were recorded via a video based eye-tracker with a sampling
302 rate of 500hz (Eyelink 2, SR research). Stimuli were presented via Experiment Builder
303 software [25]. The presentation duration of stimuli in this task was 5000 ms and stimuli
304 subtended 5.59 x 4.19 DVA.

305 **Results**

306 **Aggregated Social Bias**

307 Inspection of Figure 4 reveals a pattern of results that very closely mirror those
308 obtained from Dataset 1. There was again the same main effect of AOI $\chi^2(1) = 91.40$, p
309 $<.001$ and interaction between AOI and stimulus type $\chi^2(1) = 28.61$, $p <.001$ (Figure 4a).
310 The bias for social images was similarly larger in the intact condition ($\beta = 0.13$) than
311 scrambled condition ($\beta = 0.04$). Adding EQ to the model revealed the same 3 way

312 interaction between AOI, stimulus type and EQ $\chi^2 (1) = 18.21, p < .001$. Higher EQ was
313 associated with a larger social bias for intact stimuli, but not scrambled stimuli (Figure 4b).

314 **Time-course of Social Bias**

315 We used the same data reduction strategy as reported for Dataset 1. We removed
316 2.85% trials due to trackloss and again removed data from the first 100 ms timebin. No
317 association was detected between EQ and the number of remaining data points when this
318 cleaning strategy was applied $r (67) = -.003, p = .981$. The forward selection strategy
319 revealed that a model involving AOI and a linear and quadratic time regressors as fixed
320 effects (Figure 4c) again provided the best fit to the data (AIC -9639.3) and had the best
321 generalisation performance (see supplementary material S6).

322 **Effect of Empathy**

323 An effect of EQ as a predictor of social bias was detected within a cluster from 2800 -
324 5000ms (*corrected* $p = .009$ - Figure 4d). We again tested models that added EQ as a fixed
325 effect to our initial model of the global data. The reduced interactive model again improved
326 model fit $\chi^2 (2) = 335.98, p < .001$. Moreover, a fully interactive model further improved on the
327 reduced interactive model $\chi^2 (4) = 85.14, p < .001$. EQ was primarily predictive of social bias
328 towards the end of the trial (Figure 4d).

329 An analysis of switch latencies did not detect an interaction between initial AOI and
330 EQ $\chi^2 (1) = 3.52, p = .060$, but the effect was similar in magnitude and direction to that
331 observed in Dataset 1. Higher EQ was again associated with later switching from the social
332 AOI relative to from the nonsocial AOI (Figure 4e, Figure 4f).

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INSERT FIGURE 4 HERE

335

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Discussion

337 In this study our major novel contributions were as follows: We i) provide an explicit
338 model of the time course of social attention, ii) determine how the parameters of this model

339 are modulated by social trait characteristics of the observer iii) test this model by making
340 quantitative predictions about the allocation of an individual's gaze over time. Across two
341 large datasets, we found a number of similar findings. i) Observers exhibit a robust gaze
342 bias towards social images ii) EQ is reliably associated with an increase in this bias iii) This
343 effect of EQ is not time invariant - a model that allowed empathy to interact with the temporal
344 components of the gaze bias provided a superior fit to a model that assumed a time-
345 invariant effect of empathy. Specifically, empathy was found to reliably maintain gaze bias
346 towards social images after prolonged viewing. iv) Higher EQ was associated with less
347 frequent, and later switching from an initially fixated social image.

348 At the most fundamental level, our finding that gaze behavior is predicted by the
349 social trait characteristics of the observer emphasises that the mechanisms underlying social
350 attention are deeply enmeshed with other aspects of social cognition. The dynamic influence
351 of empathy on gaze behavior suggests that empathy is not a passive affective resonance
352 with the emotions of others and that wider contextual influences play feed-forward roles in
353 how emotions are perceived and experienced. This fits with neurocognitive theories of
354 empathy, which propose that empathy is implemented by a network of recursively connected
355 cortical and subcortical sites [26]. It also fits well with multi-stage models of empathy, which
356 propose that prolonged attention to social stimuli reflects a form of evidence gathering so
357 that appropriate empathic responses can be generated [27,28].

358 Our findings appear consistent with recent pharmacological work, which indicates
359 that administration of oxytocin (associated with the experience of empathy in humans and
360 mesolimbic dopaminergic activity involved in responding to rewards) predicts maintained
361 periods of eye-contact in Macaque monkeys [14]. We speculate the similarity of these
362 findings with our own reflect some common mechanism that promotes prolonged perceptual
363 selection of socially relevant inputs. Computational models of alternative forced choice
364 behavior have been proposed that explicitly relate gaze behavior to value coding. The 'gaze
365 cascade model' proposes that gaze and value coding mutually interact, resulting in an
366 increased gaze towards preferred stimuli over time [29]. A consistent observation from both

367 of our datasets is that trait empathy is better able to predict gaze toward social rewards
368 towards the end of the trial. One potential interpretation of this observation is that trait
369 empathy is related to enhanced motivational salience of social stimuli. By extension, we
370 speculate that the individual differences in the temporal evolution of eye-movement behavior
371 observed in our study reflects some online behavioral correlate of the value-coding process.
372 This inference relies on electrophysiological studies that show value-coding is a dynamic
373 process, and requires accumulation of evidence over time [30]. This interpretation of
374 empathy being related to the value coding of social rewards is also consistent with the
375 observation that higher empathy is associated with greater reward-related striatal activation
376 in response to socially stimuli [30]. Our free-viewing task, of course, did not require
377 observers to make an explicit choice between two stimuli. Recent computational modeling of
378 binary choice behavior indicates that impressive predictions of choice behavior can be
379 generated by models that incorporate gaze behavior and the reward value of competing
380 stimuli [32]. In this context, an interesting question concerns whether empathy similarly
381 predicts different trajectories of social attention and different gaze cascade effects in choice-
382 based paradigms.

383 In interpreting our findings, it is important to acknowledge that gaze behavior in
384 response to complex rewarding scenes is likely to reflect the output of many dissociable and
385 fundamental processes. As such, the pattern of results we found could also be driven by
386 some combination of component processes found to vary as a function of empathy. This
387 may include individual differences in gaze perception [33] expression recognition [34]
388 temporal integration [15] and a precedence of local over global processing [35]. Our data
389 cannot clarify the relative contribution of these factors. Moreover, gaze behavior is strongly
390 determined by low-level properties, such as luminance contrast and spatial frequency profile.
391 Although we attempted to protect against these issues with our matching procedures and
392 use of scrambled control stimuli, our stimuli are still not immune to these issues. However,
393 no study involving complex, naturalistic visual stimuli is completely resistant to these
394 potential confounds.

395 In the absence of longitudinal data, a claim about the directionality of the causal
396 relationship between empathy and social attention observed here is clearly over-reaching.
397 Based on the available developmental literature, however, there are sensible grounds for
398 proposing that some aspects of social attention precede empathy. Newborns exhibit robust
399 orienting responses to conspecific stimuli (particularly faces) [36], whereas the cognitive
400 components of empathy (such as theory of mind) emerge several years in development [37].
401 In this context, our study could motivate well-controlled developmental studies that track the
402 temporal structure of social attention across development and its shared trajectory with the
403 development of empathic abilities.

404 Our findings have several important implications for the design of future studies. We
405 observed that empathy can take effect on behavior several seconds after stimulus onset.
406 Spontaneous mimicry, related to certain components of empathy [38] can also take effect
407 several seconds after stimuli onset (e.g. in response to reward [39]). Findings like these may
408 question the sensitivity of methods that rely on much briefer stimulus exposures, such as
409 visual probe paradigms [40-42] in detecting differences between groups that vary in
410 empathic traits. There is widespread enthusiasm for the idea that electrophysiological
411 methods with high temporal resolution may further clarify the temporal brain dynamics of
412 empathy [43,44] and distinguish between competing explanatory models. Based on the
413 findings reported in this paper, we are additionally enthusiastic about the prospect of
414 paradigms that employ concurrent recording of both EEG and gaze data. Capitalising on the
415 high temporal resolution shared by these methods may lead to theoretical advancement by
416 providing insight into the time-course of the neural signatures underlying empathy and their
417 behavioral correlates. Motivated accounts of empathy suggest that observers may
418 dynamically increase or decrease attention to social cues to regulate their emotional
419 responses [28]. Paradigms that concurrently monitor gaze allocation and autonomic arousal
420 over time could explicitly test the predictions of such models.

421 In general, our data demonstrate that considering the temporal structure of gaze
422 signals may provide impetus towards enhanced behavioral phenotypes for conditions
423 marked by deficits in one or more empathy related processes (ASC, Psychopathy, Bipolar
424 Disorder, Schizophrenia [45-47]). More broadly, follow up experimentation of this variety can
425 also help us answer the more fundamental question: What features of gaze behavior
426 differentiate between individuals with and without these conditions? Failing to capitalize on
427 the high-dimensional, time-varying nature of gaze signals necessarily entails restricting the
428 information available for answering this question.

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- 432 1. Boyer P, Bergstrom B. Threat-detection in child development: An evolutionary
433 perspective. *Neurosci Biobehav Rev.* 2011 Mar;35(4):1034–41.
- 434 2. Hayden BY, Parikh PC, Deaner RO, Platt ML. Economic principles motivating social
435 attention in humans. *Proceedings of the Royal Society of London B: Biological*
436 *Sciences.* 2007 Jul 22;274(1619):1751–6.
- 437 3. Chevallier C, Kohls G, Troiani V, Brodtkin ES, Schultz RT. The Social Motivation Theory
438 of Autism. *Trends Cogn Sci.* 2012-4;16(4):231–9.
- 439 4. Adams RB Jr, Adams RB, Ambady N, Shimojo S, Nakayama K. The Science of Social
440 Vision: The Science of Social Vision. OUP USA; 2011. 471 p.
- 441 5. Hafri A, Trueswell JC, Strickland B. Encoding of event roles from visual scenes is rapid,
442 spontaneous, and interacts with higher-level visual processing. *Cognition.* 2018 Jun
443 1;175:36–52.
- 444 6. Klein JT, Shepherd SV, Platt ML. Social Attention and the Brain. *Curr Biol.* 2009 Nov
445 3;19(20):R958–62.
- 446 7. Chita-Tegmark M. Social attention in ASD: A review and meta-analysis of eye-tracking
447 studies. *Res Dev Disabil.* 01/2016;48:79–93.
- 448 8. Klin A, Lin DJ, Gorrindo P, Ramsay G, Jones W. Two-year-olds with autism orient to
449 non-social contingencies rather than biological motion. *Nature.* 2009 May
450 14;459(7244):257–61.
- 451 9. Pierce K, Marinero S, Hazin R, McKenna B, Barnes CC, Malige A. Eye Tracking
452 Reveals Abnormal Visual Preference for Geometric Images as an Early Biomarker of an
453 Autism Spectrum Disorder Subtype Associated With Increased Symptom Severity. *Biol*
454 *Psychiatry.* 2016 Apr 15;79(8):657–66.
- 455 10. Fischer J, Koldewyn K, Jiang YV, Kanwisher N. Unimpaired Attentional Disengagement
456 and Social Orienting in Children with Autism. *Clin Psychol Sci.* 2014 Mar;2(2):214–23.
- 457 11. Shah P, Gaule A, Bird G, Cook R. Robust orienting to protofacial stimuli in autism. *Curr*
458 *Biol.* 2013 Dec 16;23(24):R1087–8.
- 459 12. Chakrabarti B, Haffey A, Canzano L, Taylor CP, McSorley E. Individual differences in
460 responsivity to social rewards: Insights from two eye-tracking tasks. *PLoS One.* 2017
461 Oct 18;12(10):e0185146.
- 462 13. Sasson N, Tsuchiya N, Hurley R, Couture SM, Penn DL, Adolphs R, et al. Orienting to
463 social stimuli differentiates social cognitive impairment in autism and schizophrenia.
464 *Neuropsychologia.* 2007 Jun 18;45(11):2580–8.
- 465 14. Dal Monte O, Piva M, Anderson KM, Tringides M, Holmes AJ, Chang SWC. Oxytocin
466 under opioid antagonism leads to supralinear enhancement of social attention. *Proc*
467 *Natl Acad Sci U S A.* 2017 May 16;114(20):5247–52.
- 468 15. Nakano T, Tanaka K, Endo Y, Yamane Y, Yamamoto T, Nakano Y, et al. Atypical gaze
469 patterns in children and adults with autism spectrum disorders dissociated from
470 developmental changes in gaze behaviour. *Proc Biol Sci.* 2010 Oct 7;277(1696):2935–
471 43.

- 472 16. Chang SWC, Brent LJJ, Adams GK, Klein JT, Pearson JM, Watson KK, et al.
473 Neuroethology of primate social behavior. *Proc Natl Acad Sci U S A*. 2013 Jun 18;110
474 Suppl 2:10387–94.
- 475 17. Posner MI, Snyder CR, Davidson BJ. Attention and the detection of signals. *J Exp*
476 *Psychol*. 1980 Jun;109(2):160–74.
- 477 18. Lawrence EJ, Shaw P, Baker D, Baron-Cohen S, David AS. Measuring empathy:
478 reliability and validity of the Empathy Quotient. *Psychol Med*. 2004 Jul;34(5):911–9.
- 479 19. Baron-Cohen S, Wheelwright S. The empathy quotient: an investigation of adults with
480 Asperger syndrome or high functioning autism, and normal sex differences. *J Autism*
481 *Dev Disord*. 2004 Apr;34(2):163–75.
- 482 20. [PDF]International Affective Picture System (IAPS): Technical ... - Unifesp. Available
483 from: <https://www2.unifesp.br/dpsicobio/adap/instructions.pdf>
- 484 21. Psychology Software Tools, Inc. [E-Prime 2.0]. (2016). Retrieved from
485 <http://www.pstnet.com>.
- 486 22. eyetrackingR [Internet]. [cited 2018 Jun 7]. Available from: <http://www.eyetracking->
487 [r.com/](http://www.eyetracking-r.com/)
- 488 23. Mirman D, Dixon JA, Magnuson JS. Statistical and computational models of the visual
489 world paradigm: Growth curves and individual differences. *J Mem Lang*. 2008
490 Nov;59(4):475–94.
- 491 24. Maris E, Oostenveld R. Nonparametric statistical testing of EEG- and MEG-data. *J*
492 *Neurosci Methods*. 2007 Aug 15;164(1):177–90.
- 493 25. SR Research Experiment Builder 1.10.165 [Computer software]. (2011). Mississauga,
494 Ontario, Canada: SR Research Ltd.
- 495 26. Decety J. The neurodevelopment of empathy in humans. *Dev Neurosci*. 2010 Aug
496 31;32(4):257–67.
- 497 27. Bird G, Viding E. The self to other model of empathy: providing a new framework for
498 understanding empathy impairments in psychopathy, autism, and alexithymia. *Neurosci*
499 *Biobehav Rev*. 2014 Nov;47:520–32.
- 500 28. Zaki J. Empathy: a motivated account. *Psychol Bull*. 2014 Nov;140(6):1608–47.
- 501 29. Shimojo S, Simion C, Shimojo E, Scheier C. Gaze bias both reflects and influences
502 preference. *Nat Neurosci*. 2003 Nov 9;6:1317.
- 503 30. Kim H, Sul JH, Huh N, Lee D, Jung MW. Role of Striatum in Updating Values of Chosen
504 Actions. *J Neurosci*. 2009 Nov 25;29(47):14701–12.
- 505 31. Chakrabarti B, Bullmore E, Baron-Cohen S. Empathizing with basic emotions: common
506 and discrete neural substrates. *Soc Neurosci*. 2006;1(3-4):364–84.
- 507 32. Krajbich I, Armel C, Rangel A. Visual fixations and the computation and comparison of
508 value in simple choice. *Nat Neurosci*. 2010 Oct;13(10):1292–8.
- 509 33. Pantelis PC, Kennedy DP. Deconstructing atypical eye gaze perception in autism
510 spectrum disorder. *Sci Rep*. 2017 Nov 8;7(1):14990.

- 511 34. Harms MB, Martin A, Wallace GL. Facial emotion recognition in autism spectrum
512 disorders: a review of behavioral and neuroimaging studies. *Neuropsychol Rev.* 2010
513 Sep;20(3):290–322.
- 514 35. Dakin S, Frith U. Vagaries of visual perception in autism. *Neuron.* 2005 Nov
515 3;48(3):497–507.
- 516 36. Johnson MH, Dziurawiec S, Ellis H, Morton J. Newborns' preferential tracking of face-
517 like stimuli and its subsequent decline. *Cognition.* 1991 Aug 1;40(1):1–19.
- 518 37. Leslie AM, Friedman O, German TP. Core mechanisms in “theory of mind.” *Trends*
519 *Cogn Sci.* 2004 Dec 1;8(12):528–33.
- 520 38. Pfeifer JH, Iacoboni M, Mazziotta JC, Dapretto M. Mirroring others' emotions relates to
521 empathy and interpersonal competence in children. *Neuroimage.* 2008 Feb
522 15;39(4):2076–85.
- 523 39. Sims TB, Van Reekum CM, Johnstone T, Chakrabarti B. How reward modulates
524 mimicry: EMG evidence of greater facial mimicry of more rewarding happy faces.
525 *Psychophysiology.* 2012 Jul;49(7):998–1004.
- 526 40. Zhao X, Zhang P, Fu L, Maes JHR. Attentional biases to faces expressing disgust in
527 children with autism spectrum disorders: an exploratory study. *Sci Rep.* 2016 Jan
528 13;6:19381.
- 529 41. Moore DJ, Heavey L, Reidy J. Attentional Processing of Faces in ASD: A Dot-Probe
530 Study. *J Autism Dev Disord.* 2012 Oct 1;42(10):2038–45.
- 531 42. Quintana DS, Westlye LT, Hope S, Nærlund T, Elvsåshagen T, Dørum E, et al. Dose-
532 dependent social-cognitive effects of intranasal oxytocin delivered with novel Breath
533 Powered device in adults with autism spectrum disorder: a randomized placebo-
534 controlled double-blind crossover trial. *Transl Psychiatry.* 2017 May 23;7(5):e1136.
- 535 43. Neumann DL, Westbury HR. The psychophysiological measurement of empathy.
536 *Psychology of empathy.* 2011;119–42.
- 537 44. Suzuki Y, Galli L, Ikeda A, Itakura S, Kitazaki M. Measuring empathy for human and
538 robot hand pain using electroencephalography. *Sci Rep.* 2015 Nov 3;5:15924.
- 539 45. Derntl B, Finkelmeyer A, Toygar TK, Hülsmann A, Schneider F, Falkenberg DI, et al.
540 Generalized deficit in all core components of empathy in schizophrenia. *Schizophr Res.*
541 2009 Mar;108(1-3):197–206.
- 542 46. Jones AP, Happé FGE, Gilbert F, Burnett S, Viding E. Feeling, caring, knowing:
543 different types of empathy deficit in boys with psychopathic tendencies and autism
544 spectrum disorder: Comparing empathy deficits in boys with psychopathic tendencies
545 and ASD. *J Child Psychol Psychiatry.* 2010 Nov 13;51(11):1188–97.
- 546 47. Shamay-Tsoory S, Harari H, Szepsenwol O, Levkovitz Y. Neuropsychological evidence
547 of impaired cognitive empathy in euthymic bipolar disorder. *J Neuropsychiatry Clin*
548 *Neurosci.* 2009 Winter;21(1):59–67.

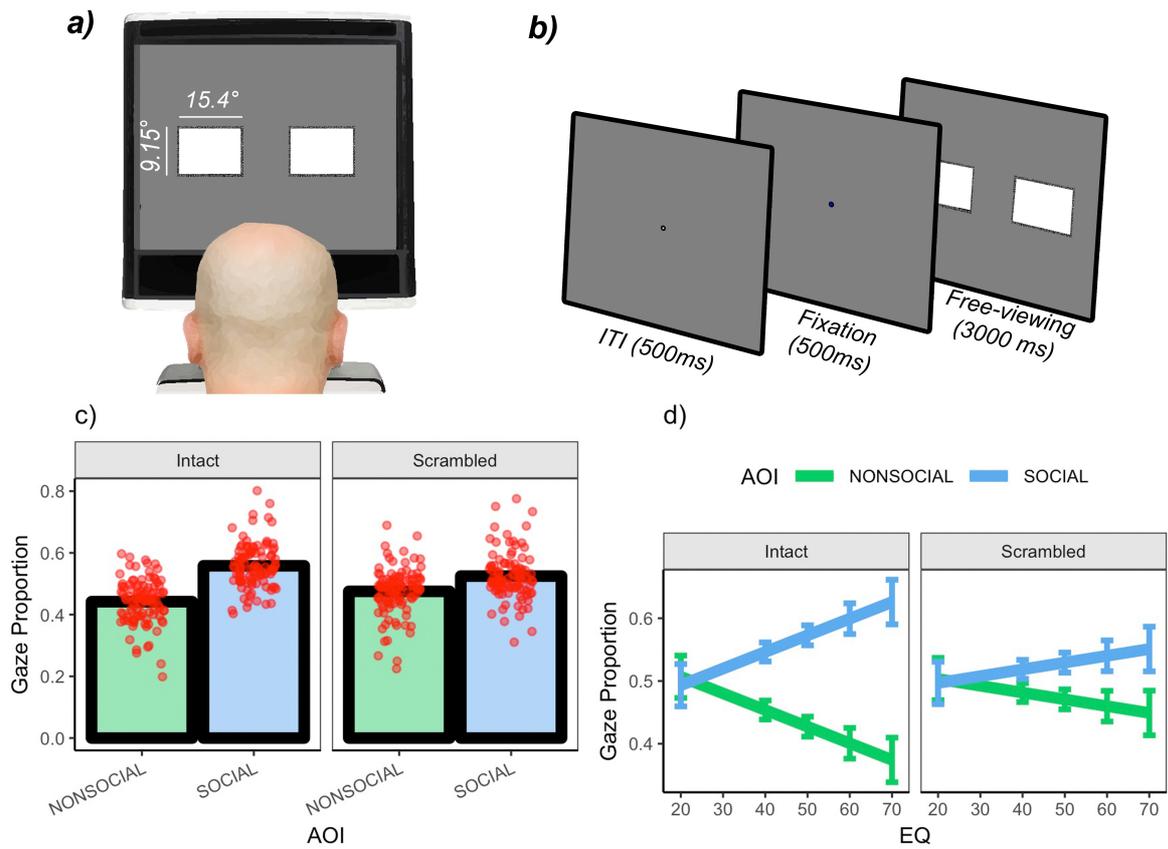
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Figures



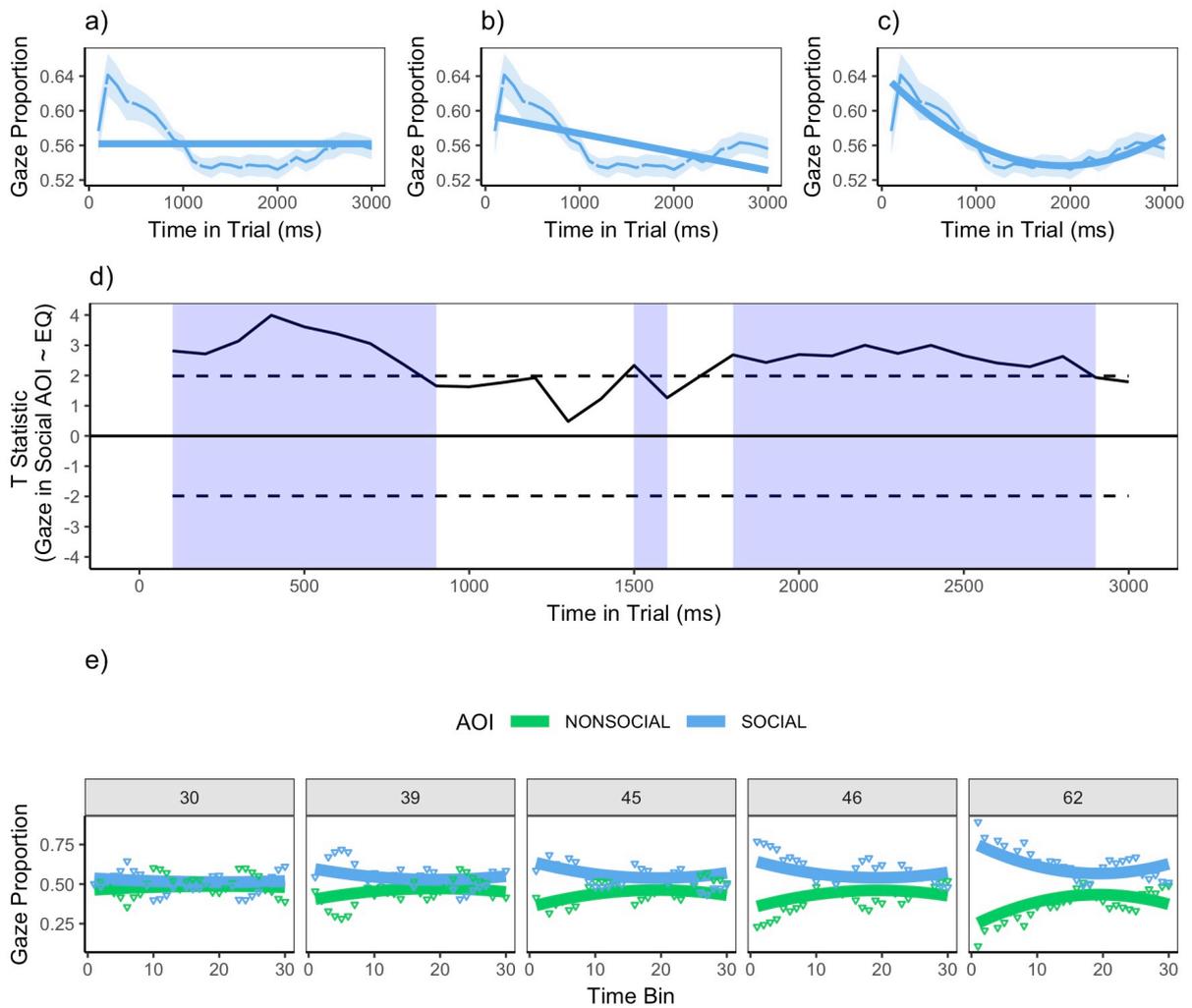
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554 *Figure 1. a) Schematic of experimental setup and b) trial sequence. c) Gaze proportion as a*

555 *function of AOI and stimulus type. Red points indicate individual data. d) Gaze proportion as*

556 *a function of AOI, stimulus type and EQ. Error bars are +/- 1 SEM.*

557



558

559 *Figure 2.* a) Shows the time series fit to the gaze proportion into the social AOI with only AOI

560 as a fixed effect (no effect of time). b) Shows a fit to the same data with AOI and a linear

561 time regressor as fixed effects. c) Shows the the data fit with AOI and linear and quadratic

562 time regressors. d) Shows *t* statistics for the test that EQ is a linear predictor of gaze

563 proportion into the social AOI within each 100ms time bin. Shaded areas demarcate the time

564 bins wherein the statistic reaches the (uncorrected) threshold for rejecting the null

565 hypothesis. e) Shows predictions of the fully interactive model for 5 observers. The panel

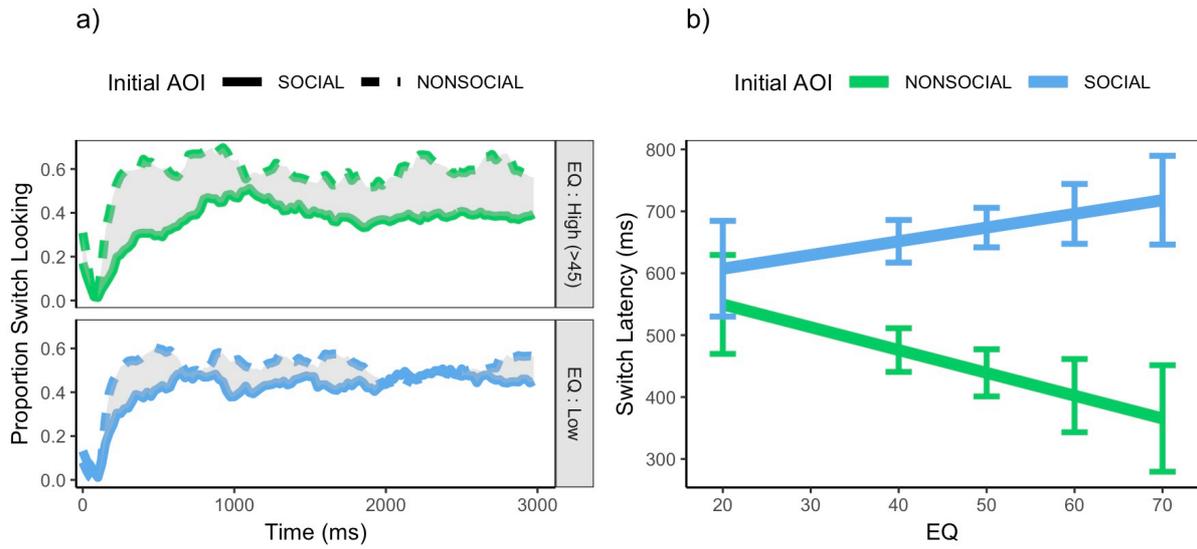
566 headers indicate the observer's EQ score. Solid lines are model predictions, points are the

567 empirical data.

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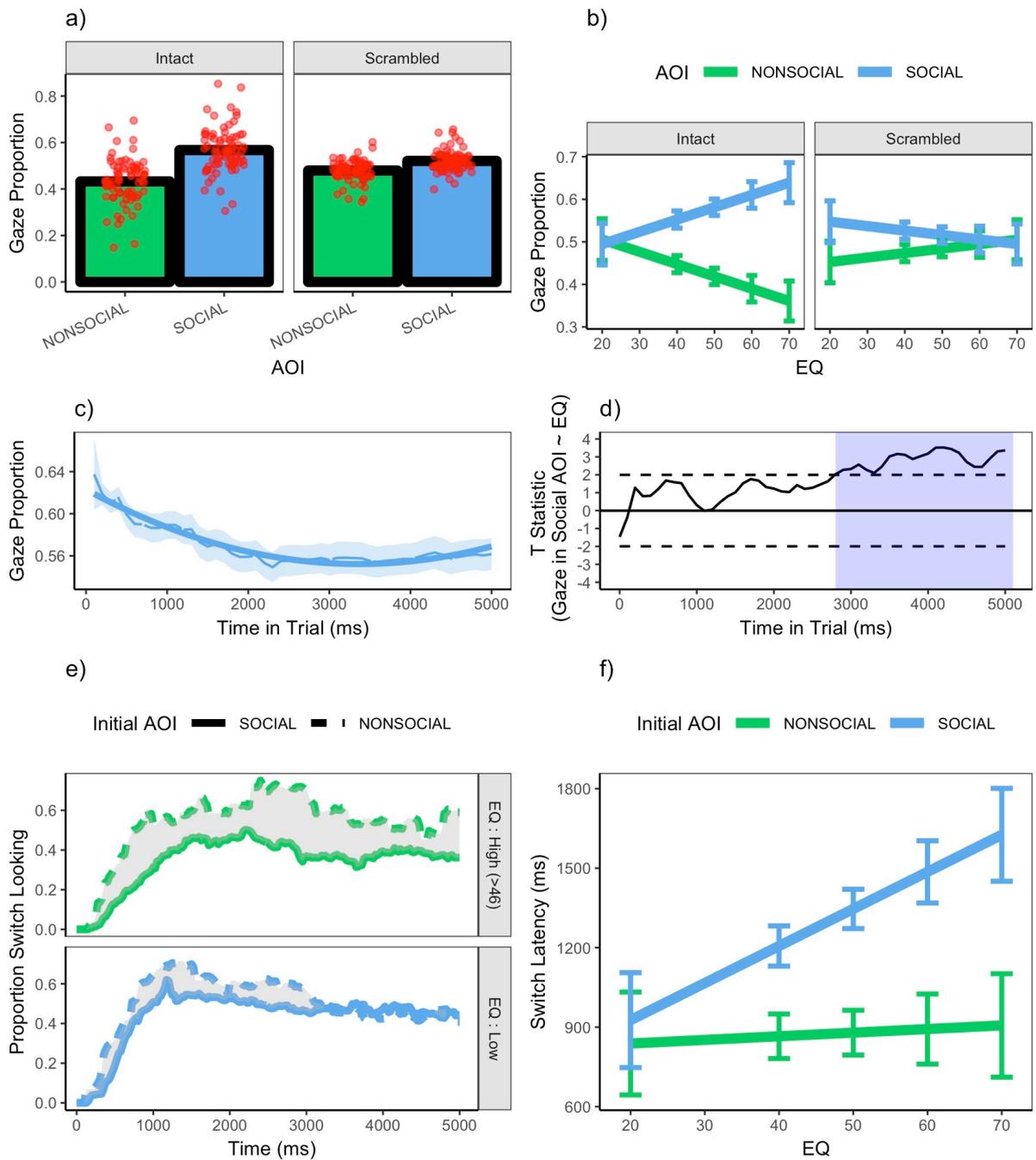


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573 *Figure 3.* a) Shows proportion of observers who switched to the alternate AOI as a function
 574 of initial AOI, EQ (median split) and time b) Shows switch latency as a function of initial AOI
 575 and EQ. Error bars are ± 1 SEM.

576



578

579 *Figure 4.* a) Gaze proportion as a function of AOI and stimulus type. Red points indicate
 580 individual data. b) Gaze proportion as a function of AOI, stimulus type and EQ. Error bars
 581 are +/- 1 SEM. c) Shows the fit to gaze proportion time series with AOI and a linear and
 582 quadratic time regressors as fixed effects. Data is shown for the social AOI. d) Shows *t*
 583 statistics for the test that EQ is a linear predictor of gaze proportion into the social AOI within
 584 each 100ms time bin. Shaded areas demarcate the time bins wherein the statistic reaches

585 the (uncorrected) threshold for rejecting the null hypothesis. e) Shows proportion of
586 observers who switched to the alternate AOI as a function of initial AOI and EQ (median
587 split) f) Shows switch latency as a function of initial AOI and EQ. Error bars are +/- 1 SEM.

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