

1 **Curious Choices: Infants' moment-to-moment information sampling is driven by their**
2 **exploration history**

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Research highlights

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- A powerful new paradigm enabling active exploration in a controlled environment.

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- Infants' curiosity-driven exploration within this paradigm was non-random.

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- Infants generated different sampling patterns, from explorative to exploitative.

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- The largest emerging group, however, sampled information from both categories.

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- Exploration history and pre-switch behaviour predicted exploratory switching.

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Abstract

Infants explore the world around them based on their intrinsically motivated curiosity. However, the cognitive mechanisms underlying such curiosity-driven exploratory behaviour remain largely unknown. Here, infants could freely explore two novel categories, triggering a new exemplar from a category by fixating on either of the two associated areas on a computer screen. This gaze-contingent design enabled us to distinguish between exploration – switching from one category to another – and exploitation – consecutively triggering exemplars from the same category. Data from 10-12-month-old infants ($N=68$) indicated that moment-to-moment sampling choices were non-random but guided by the infants' exploration history. Self-generated sequences grouped into three clusters of brief yet explorative, longer exploitative, and overall more balanced sampling patterns. Bayesian hierarchical binomial regression models indicated that across sequence patterns, infants' longer trigger time, shorter looking time, and more gaze-shifting were associated with trial-by-trial decisions to disengage from exploiting one category and making an exploratory switch, especially after consecutively viewed stimuli of high similarity. These findings offer novel insights into infants' curiosity-driven exploration and pave the way for future investigations, also regarding individual differences.

Keywords: infant curiosity, information sampling, exploration-exploitation, gaze-contingent eye-tracking

45 **Curious Choices: Infants' moment-to-moment information sampling is driven by their**
46 **exploration history**

47 Curiosity is considered the driving force behind exploration, discovery, and learning,
48 motivating us to seek out new experiences, knowledge, and skills. It is, therefore, a crucial
49 developmental factor from infancy onward, which has also been linked to positive outcomes
50 later in life. Although there are various theoretical approaches to defining curiosity, they mostly
51 agree that it reflects an intrinsic motivation to acquire information to enhance our
52 understanding of the world (see reviews Bazhydai et al., 2021; Begus & Southgate, 2018; Kidd
53 & Hayden, 2015; Reio Jr. et al., 2006; but see also Dubey & Griffiths, 2020). It manifests itself
54 in exploratory behaviours; however, little is known about what drives moment-to-moment
55 choices of such curiosity-based exploration in infants. In this study, we aimed to capture
56 infants' active exploration within a controlled environment employing state-of-the-art gaze-
57 contingent eye-tracking methodology.

58 **1.1 Infants explore actively**

59 Infants are active explorers who help shape their own learning experiences (e.g., Piaget,
60 1970; Smith et al., 2018). These behaviours manifest themselves in, for example, visual and
61 tactile exploration, but also in requesting information from others by pointing and later through
62 verbal communication. Such exploration opportunities dramatically evolve throughout the first
63 two years of life with infants developing a variety of new skills – gross-motor, fine-motor, and
64 communicative – supporting ever more sophisticated exploratory behaviours and offering new
65 perspectives on their immediately accessible physical (Adolph & Hoch, 2019) and social
66 (Karasik et al., 2014) environments. In fact, infants autonomously adapt their exploration
67 strategies to characteristics of their environment, such as employing different actions on objects
68 based on their properties (e.g., Bourgeois et al., 2005; Fontenelle et al., 2007), selectively
69 preferring an action that previously provided new information, travelling farther in a room with

70 toys than without (Hoch et al., 2019), and selectively referring to the more informative adult
71 when seeking an answer in a situation of referential uncertainty (Bazhydai et al., 2020). Infants
72 also showed increased focus, longer-lasting exploration, and better learning when the course
73 of play or interactive exploration followed their attention (C. Chen et al., 2021; Schatz et al.,
74 2022; Suarez-Rivera et al., 2019; Tamis-LeMonda et al., 2013) rather than the caregiver's
75 redirection (Bono & Stifter, 2003; Mendive et al., 2013; Pridham et al., 2000). Similarly, there
76 seems to be a learning advantage for novel labels when these are presented in response to the
77 infant's pointing gesture (Begus et al., 2014; Lucca & Wilbourn, 2019) and object-directed
78 vocalisations (Goldstein et al., 2010) which are interpreted as communicative indices of
79 information-seeking. Together, these studies highlight how infants use their available skills to
80 explore the world on their own terms and benefit from doing so (see also Mani & Ackermann,
81 2018). An important question within developmental research which has only recently started
82 to gain much-needed attention is to understand the mechanisms underlying infants' dynamic
83 exploration as well as why it leads to these advantages (Begus & Southgate, 2018; Kidd &
84 Hayden, 2015).

85 **1.2 Exploration as a function of environment knowledge and learning mechanism**

86 To better understand infant exploration, we need to consider which factors may guide
87 infants' exploratory choices dynamically. This includes both previous experience with the
88 environment as well as the mechanism by which that knowledge affects subsequent behaviour.
89 Findings from looking-time studies suggest both novelty (e.g., Fantz, 1964; Siqueland &
90 DeLucia, 1969; Stahl & Feigenson, 2015) and familiarity (e.g., Bushnell, 2001; DeCasper &
91 Spence, 1986; Gaither et al., 2012) to be key characteristics to predict infants' engagement.
92 Studies investigating infants' preferences for complexity found that infants were most likely to
93 stay engaged at intermediate complexity levels ("Goldilocks effect", e.g., Berlyne, 1960; Kidd

94 et al., 2012, 2014; Kidd & Hayden, 2015) whereas infants disengaged from sequences which
95 were too predictable (Addyman & Mareschal, 2013) or unlearnable (Gerken et al., 2011).

96 A mechanism proposed to explain these findings is learning progress maximisation
97 (e.g., Altmann et al., 2021; Oudeyer et al., 2007; Twomey & Westermann, 2018) where
98 exploration is driven by making intrinsically rewarding learning progress. Findings from adult
99 populations where higher levels of curiosity have been linked to stronger activation in the
100 dopaminergic brain circuits (Gruber et al., 2014; Kang et al., 2009) support the notion of its
101 intrinsically rewarding nature. Computational models have shown that learning progress can
102 predict infants' looking and looking away above and beyond predictability or surprise alone
103 (Poli et al., 2020). They have also highlighted the importance of a moment-to-moment
104 perspective because what maximises learning progress is dependent on the learner's current
105 knowledge and changes dynamically with every learning experience and knowledge update
106 (Twomey & Westermann, 2018). It is to be noted that learning progress thereby offers a
107 comparatively lean approach to interpreting curiosity as a psychological construct (Goupil &
108 Proust, 2023; Poli et al., 2024). Furthermore, how much learning progress is being made by
109 engaging with something is not only based on the available information in the environment but
110 also on the degree to which it is being encoded. This is in line with previous research that found
111 infants' looking preferences to be best explained by the degree of exposure and encoding rather
112 than the distinction between novelty or familiarity alone (e.g., Hunter & Ames, 1988; Oakes et
113 al., 1991; Rose et al., 1982). Thus, to understand infants' dynamic, curiosity-driven exploration
114 we need to consider the interplay between what information the environment offers but also
115 how the infant engages with that information in order to predict and understand their successive
116 sampling choices.

117 **1.3 Need for a new paradigm**

118 Studies on infant exploration have thus far followed one of two main methodological
119 approaches: either employing largely unstructured designs such as free play sessions, using
120 observation and video recordings or head-mounted cameras and eye-tracking (e.g., Hoch et al.,
121 2019; Rodriguez & Tamis-LeMonda, 2011; Slone et al., 2019; Yu & Smith, 2012), or
122 controlled laboratory settings to capture visual exploration and engagement across predefined
123 groups of stimuli and sequences (Addyman & Mareschal, 2013; X. Chen et al., 2022; Kidd et
124 al., 2012; Poli et al., 2020). While both allow for invaluable insights into infant exploration,
125 they do represent two ends of a continuum. Free play studies provide rich data on more
126 descriptive characteristics of infants' curiosity-driven exploration, but the emerging variability
127 poses difficulties in deriving precise mechanistic accounts. On the other hand, structured
128 studies allow for precise manipulation of the provided information to disentangle underlying
129 factors explaining exploration behaviour, such as predictability or stimulus similarities, but do
130 not capture the active choices infants would make in more natural settings. Here we propose a
131 paradigm which combines these approaches by using gaze-contingent eye-tracking – where the
132 visual display changes in response to the infant's fixation. This approach enables infants to
133 determine the sequence and timing of their exploration within an otherwise controlled
134 environment.

135 Previous studies employing gaze-contingent eye-tracking have shown that infants
136 quickly learn the association between looking towards a specific area on the screen and certain
137 types of information or stimuli being presented (Bazhydai et al., 2022; Keemink et al., 2019;
138 Miyazaki et al., 2015; Sučević et al., 2021; Tummeltshammer et al., 2014; Wang et al., 2012;
139 Zettersten, 2020). It is therefore a powerful method to implement an active component into a
140 structured study design. In fact, similar to our conceptualisation, recent studies (Bazhydai et

141 al., 2022; Zettersten, 2020) also employed gaze-contingent eye-tracking as a way to investigate
142 infants' active sampling and exploratory behaviours.

143 In our new 'Curious Choices' paradigm, infants can discover interactive information
144 sources in the environment and thereby freely explore two novel categories by fixating on an
145 associated area on the screen, triggering the presentation of a novel exemplar from the
146 respective category. This way, infants can self-generate exploratory sequences which provide
147 data for more general characteristics of the emerging exploration patterns, but also allow for
148 mechanistic investigations regarding infants' dynamic sampling choices based on the
149 information sources they discovered and how they engaged with the encountered, varying
150 visual information.

151 **1.4 Exploration-exploitation framework**

152 The 'Curious Choices' paradigm allows infants to create sequences for receiving
153 information about two novel categories, where every trigger can be conceptualised as a
154 decision to either continue viewing exemplars from one category or to switch over to the other.
155 A useful framework to explain and predict such dynamic choices of 'staying' versus
156 'switching' is the exploration-exploitation trade-off (Charnov, 1976). Applied to curiosity-
157 driven exploration, this trade-off would predict the agent to exploit an intrinsically rewarding
158 learning opportunity (in other words the focused exploration of a known information source),
159 but to disengage when learning progress subsides. Instead, the agent would then turn to explore
160 the environment more broadly in pursuit of other options worth exploiting (e.g., Oudeyer &
161 Smith, 2016). Making such an exploratory switch requires cognitive effort to redirect one's
162 attention (Pelz et al., 2015) leading to a baseline tendency to exploit (Hayden et al., 2011).
163 Accordingly, the new paradigm allows us to evaluate these assumptions by linking the
164 exploration-exploitation trade-off to the mechanism of learning progress maximisation. While
165 the exploration-exploitation framework has been applied to investigate information seeking in

166 adults often employing a k-armed bandit paradigm where the participant can sample from k-
167 amount of reward sources (Averbeck, 2015), these studies were mainly focused on maximising
168 external rewards (e.g., Daw et al., 2006; Somerville et al., 2017). Furthermore, only recently
169 work has started to study children who had long been assumed to explore un-systematically
170 (Blanco & Sloutsky, 2020; Schulz et al., 2019). For instance, in a computerised task, Meder et
171 al. (2021) found that 4- to 9-year-old children explored the environment in an uncertainty-
172 directed manner to maximise their rewards, with random exploration decreasing with age.
173 Regarding earlier emerging, manual exploration in the absence of external rewards, Karmazyn-
174 Raz & Smith (2023) found a systematic toy selection where 21-month-olds showed exploitative
175 engagement with a selection of objects but only rarely engaged with all others. In summary,
176 the exploration-exploitation trade-off lends itself to predicting dynamic exploration choices
177 and, together with the novel paradigm, offers new insights into the systematicity even of
178 infants' active information sampling.

179 **1.5 The current study**

180 The aim of the current study was to investigate infants' curiosity-driven exploration of
181 two unfamiliar categories within a controlled environment. For this, we developed and
182 employed the Curious Choices paradigm, comparable to a 2-armed bandit task. Here, 10-12-
183 month-old infants were introduced to two Fribble species (TarrLab) which are novel stimuli
184 with animal-like features (Williams, 1998). Two identical "houses" were presented on a
185 computer screen, and at each trial, a new exemplar from one of the categories was revealed if
186 the infant fixated on the corresponding house. This way, we could explore how intrinsic
187 curiosity resulted in specific exploration patterns which, in turn, captured how infants weighed
188 exploration against exploitation. Importantly, it also allowed us to disentangle behavioural and
189 environmental factors explaining their sampling choices. The age group was chosen on the
190 basis that the infants would have relevant skills such as object permanence (e.g., Bremner et

191 al., 2015) and higher-level representations guiding their looking (Kiat et al., 2022) as the novel
192 categories would not be visible unless triggered. The research questions were as follows:

- 193 1. Do infants explore non-randomly within this new paradigm?
194 2. Do group-level patterns emerge from the self-generated sequences based on how
195 exploration was weighed against exploitation?
196 3. Can dynamic exploratory choices be predicted by aspects of the infant's behavioural
197 patterns and exploration history?
198 4. Do individual-level predictors differ between the possibly emerging group-level
199 exploration patterns (combining research questions 2 and 3)?

200 **2. Methods**

201 **2.1 Participants**

202 The sample consisted of $N = 68$ typically developing infants (age range: 10-12 months,
203 $M = 11.14$, $SD = 0.52$, 50% female) from the northwest of England. Additionally, three infants
204 were excluded due to calibration problems and another infant due to not engaging with the
205 study procedure. Caregivers were reimbursed £5 for their travel and the child received a small
206 gift (book or t-shirt) for participating. Informed consent was obtained before the study
207 commenced. The study was approved by the University Faculty's research ethics committee.

208 **2.2 Materials**

209 **2.2.1 Stimuli.** Novel visual stimuli, called Fribbles, were sourced from the open
210 TarrLab repository¹. Fribbles are animal-like figures with four distinct body parts, each of
211 which comes in three variants. Two species (FA2 & FB4, see Figure 1) were chosen under the
212 consideration that none of the four body-parts was dominantly salient (Barry et al., 2014;

¹ TarrLab Stimuli at <https://sites.google.com/andrew.cmu.edu/tarrlab/stimuli?pli=1>

213 Williams, 1998). Thirty out of 81 possible stimuli per species (in the following referred to as
214 categories) were selected to capture the possible variability in stimulus similarities (differences
215 in one to four body-parts). The stimuli were standardised to a size of 400x300 pixels with the
216 exemplar presented on a white background, matched in luminosity using Adobe Photoshop.
217 For both categories, a random stimulus sequence was created determining which stimulus
218 would be presented at any given trial, if triggered, consistent across participants but
219 counterbalanced regarding their associated location. Additionally, 10 exemplars from two
220 animal categories – ducks and tortoises on white background (532x531 pixels) – were selected
221 for the warm-up phase. Per phase, two identical houses functioned as ‘buttons’ triggered by
222 fixations.

223 **2.2.2 Apparatus & Procedure.** Prior to the appointment, caregivers were asked to
224 complete a short infant curiosity questionnaire (Altmann et al., 2024) online which will not be
225 further analysed in the current paper as it was still in the process of validation by the time of
226 submission. At the lab, infants either sat on their caregiver’s lap (77%) or in a high-chair (23%),
227 approximately 60 cm away from the screen (24-inch, resolution of 1920x1080 pixels).
228 Fixations were recorded using a TobiiX120 eye tracker positioned below the screen, with a
229 gaze sampling rate of 60 Hz and a five-point calibration. The experimenter ensured adequate
230 calibration quality, paid close attention to the infants’ behaviours throughout the testing, and
231 recorded if there were any concerns about a mismatch between looks and triggers.
232 Consequently, each identified case was checked leading to the three excluded infants reported
233 in the participant section. Caregivers were explicitly instructed not to interrupt or influence
234 their child’s behaviour.

235 The experiment was structured into two parts, warm-up and exploration, each following
236 a similar procedure: an introduction phase and a gaze-contingent phase. In the warm-up
237 introduction, a female voice said in child-directed speech ‘There are two *houses*. *Look* who

238 lives in the houses!’ while in the exploration introduction, the same voice said “Here are two
239 *new* houses. Look who lives in *these* houses!”, intended to direct the infants’ attention towards
240 the screen. This was followed by a video clip showing all exemplars (animals in the warm-up,
241 Fribbles in the exploration phase) surrounding their respective house for one second, before
242 synchronously moving into those houses over the duration of five seconds, accompanied by
243 some ‘squeaky’ noises. Which categories were associated with which side in either part was
244 counterbalanced across participants.

245 In the gaze-contingent phases, infants could then trigger new exemplars from either
246 category by fixating on the respective house for 700ms. This threshold was based on previous
247 gaze-contingent designs choosing between 500 and 700ms with infants aged between 6 and 23
248 months (Bazhydai et al., 2022; Sučević et al., 2021; Wang et al., 2012; Zettersten, 2020),
249 choosing a more conservative threshold to ensure more robust (less incidental) triggering.
250 Furthermore, the algorithm was specified to ignore sample-losses of less than 100ms to ensure
251 that triggering was not obstructed by the generally less stable eye tracking data infants generate.

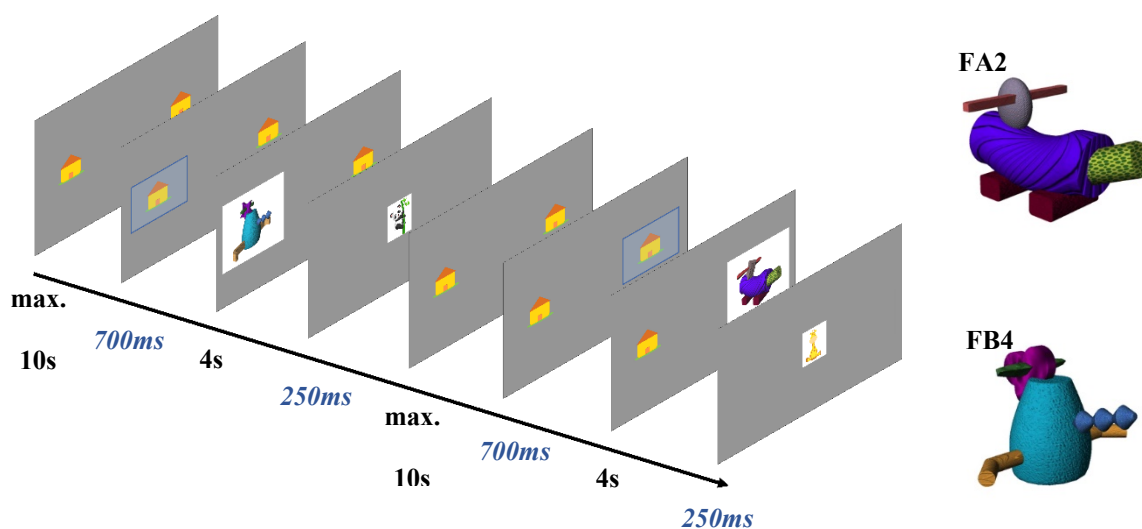
252 When a house was triggered, the next exemplar from this category was presented for
253 four seconds: increasing in size for one second as if it emerged from its respective house,
254 followed by static presentation for three seconds, while the other house was still visible (Fig.
255 1). Disappearance of the exemplar was followed by a gaze-contingent central attention getter
256 which required being fixated for 250ms to start the next trial. If the infant did not fixate on
257 either house within ten seconds, the trial was automatically terminated, registered as an empty
258 trial, and an attention getter was presented again (following Wang et al., 2012). While the
259 warm-up phase was constrained to 30 seconds (median number of warm-up triggers = 4, $M =$
260 3.5, $SD = 1.57$), the exploration phase was constrained to 30 trials (thus, a maximum of 30
261 Fribble exemplars could be triggered; median number of exploration triggers = 21.5, $M = 19.8$,
262 $SD = 9.77$).

263 The experiment ended either after 30 trials ($n = 27$) if the infant had three consecutive
 264 empty trials ($n = 12$), or if they became fussy so that the experimenter terminated the
 265 experiment during the following attention-getter phase ($n = 29$). However, this termination did
 266 not lead to the participant's exclusion but captured differences in how long infants wanted to
 267 engage with the study. Overall, the experiment lasted no longer than six minutes, and the
 268 overall visit lasted up to half an hour including time to arrive, getting accustomed to the room,
 269 as well as playtime and debriefing afterwards.

270

271 **Figure 1**

272 *Study Design*



273 *Note.* **Left:** An example sequence of two trials: when a house is triggered, an exemplar from this house
 274 is shown (coloured AOI here for illustration purposes, not visible in practice). Cursive values indicate
 275 looking time necessary to make a trigger. **Right:** Example stimuli from both novel categories: Fribble
 276 families A and B as indicated by their main body.

277

278 **2.3 Data Processing**

279 Data was processed and analysed using R (Version 4.1.2). Triggers were recoded as
 280 either a *stay-event* (triggering the same category as in the previous trial, e.g., AA) or a *switch-*

281 *event* (e.g., **AB**), whereas all first triggers were coded as *start-events* from where a decision
282 could be made to stay or switch. Then, *runs* of consecutive triggers towards each category were
283 computed. For instance, a sequence of AABBBBA is made up of three runs: the first and third
284 in category A (lengths of 2 and 1 respectively) and the second of length 4 in category B. Empty
285 trials were coded to end a run as the infant disengaged for at least 10 seconds; thus, returning
286 to exploration, even to the same category, implies renewed engagement, so the first trigger was
287 then again coded as a *start-event*.

288 The eye-tracking raw data was initially pre-processed through two rounds of
289 interpolation (e.g., Hessels et al., 2017). The first round identified blinks and smaller technical
290 glitches by interpolating over missing samples of less than 100 ms to connect the preceding
291 and subsequent looking coordinates (R package ‘eyetools’, Version 0.4.6). The second round
292 connected fixations on certain areas of interest (AOI) if they were interrupted by fixations to
293 another area shorter than 50ms, most likely to reflect technical glitches rather than short looks
294 away (e.g., Hessels et al., 2017). AOIs were defined per screen phase: attention getter in the
295 *centre*, house and stimulus *left*, as well as house and stimulus *right*, whereas fixations to non-
296 relevant areas were coded as *screen*, and *NA* if off-screen. Continuous looks towards each AOI
297 were computed, where looks shorter than 100 ms were excluded as the minimal window-size
298 (e.g., Chen et al., 2022). The remaining continuous looks were then added for total looking
299 time per AOI and trial-phase.

300 **2.4 Measures**

301 **2.4.1 Overall engagement.** Overall engagement was defined as the number of triggers
302 the infant made over the course of the exploration phase (min. 1, max. 30).

303 **2.4.2 Switch-proportion.** Switch-proportion was defined as the proportion of valid
304 triggers which were decisions to switch from the current category to the other one (e.g., a
305 sequence of AA**BA**BB would have a switch-proportion of 3/6 or 0.5 as the decisions to switch

306 or stay begin at the second trigger). Higher values indicate more switching, thus, stronger
307 explorative tendencies.

308 **2.4.3 Category entropy.** Shannon entropy (H) is an information theoretical uncertainty
309 index which can quantify the amount of information contained in a random variable based on
310 observed event counts (Shannon, 1948). Here, it was computed as the negative logarithm of
311 the observed probability to trigger either category, characterising the overall systematicity of
312 the sequence. Entropy becomes maximal ($H=1$) for sequences where, based on previous
313 observations, either choice is equally likely (i.e., random) and thus, maximally informative. It
314 becomes minimal ($H=0$) for perfectly predictable sequences, where each choice is minimally
315 informative as it is expected.

316 Both switch-proportion and category entropy provide unique information about the
317 participant's exploration. For example, the switch-proportion captures structural dynamics
318 neglected within category entropy (e.g., same H for AAABB and ABABA), whereas category
319 entropy factors in the number of observations (e.g., larger H for ABBBBB than ABB).

320 **2.4.4 Behavioural Engagement.** **Trigger time** was the time from the moment the two
321 houses appeared on screen (after the offset of the central attention getter) to the moment one of
322 the houses was triggered. **Looking time** was the absolute duration the infant looked at the
323 triggered stimulus. **Gaze-shifts** was defined as how many times during the presentation of an
324 individual stimulus in a trial the infant shifted their gaze away from the currently displayed
325 Fribble to the other side, that is, the untriggered house.

326 **2.4.5 Stimulus Similarity.** This was defined as the subjective similarity between the
327 current stimulus and directly preceding stimulus from the same category² indicating the
328 additional amount of information about the category the current stimulus offered (more similar
329 pairs offering less new information). All variables were standardised within each participant
330 so that trial-by-trial predictions were based on differences in the individual's behaviour.

331 **2.5 Analysis Plan**

332 While these analyses and hypotheses were not pre-registered due to the novelty of this
333 paradigm and the generally exploratory nature of the study, the variables and general analyses
334 were specified and decided upon before inspecting the data. The report of the behavioural
335 switch-prediction (2.6.3.1) in addition to their interaction with the stimulus similarities
336 (2.6.3.2), however, was made ad hoc due to realising the consequently extensive reduction of
337 observations (detailed below).

338 **2.5.1 Did infants explore non-randomly?** We hypothesised that infants would explore
339 systematically, which means that their trigger choices were different from chance. To analyse
340 randomness in switching behaviour at each trial as well as their category sampling, 1000 draws
341 from a binomial distribution with a likelihood of .50 were simulated for each infant based on
342 their number of triggers. Switch proportions and category entropy were computed for each
343 draw. The simulated distributions consisted of 68000 draws for each variable, and
344 Kolmogorov-Smirnov tests were performed to determine if simulated and observed data came
345 from the same chance distribution or not.

² These scores are based on a supplementary online study with an adult sample ($N = 45$, $M_{age} = 27.41$, range = 18 to 54 years, 52.4% female) in which we obtained subjective similarity scores between all possible combinations of stimuli for each category on a scale from 1 ("not similar at all") to 7 ("extremely similar") which were significantly correlated with the number of objective differences ($r = -0.54$, $p < 0.001$); see supplementary materials S2 for more details.

346 **2.5.2. Did patterns of exploration emerge?** We hypothesised that there would be
347 variance regarding how infants structured their self-generated exploration sequences. To
348 identify emerging patterns, a cluster analysis was computed based on overall engagement,
349 switch-proportion, and category entropy, capturing quantitative and qualitative aspects of how
350 infants weighted exploration against exploitation. These variables were checked for clustering
351 using the Hopkins statistic (Hopkins, 1954) where the value of 0.89 (≥ 0.7) indicated clustering
352 in the data³. As the clustering method, we chose Partitioning Around Medoids (PAM; Kaufman
353 & Rousseeuw, 2009) which groups the data permutationally around central data-points
354 (medoids) minimising the pairwise dissimilarities between observations within clusters⁴. The
355 optimal number of clusters was determined using the R package ‘NbClust’ (Version 3.0.1), the
356 cluster analysis was conducted using the package ‘cluster’ (Version 2.1.2) and data
357 visualisation was achieved using ‘plotly’ (Version 4.10.1).

358 **2.5.3. Could trial-by-trial trigger decisions be predicted?**

359 The novel paradigm allows us to investigate both, infants’ engagement with
360 information sources in their environment, and the encountered stimuli’s effect on conjointly
361 guiding their dynamic sampling choices.

362 **2.5.3.1 Behavioural switch-prediction.** We hypothesised that behavioural indicators –
363 trigger time, looking time, and gaze shifts – would predict the decision to switch from
364 exploiting the current category to exploring the other. We expected that a decrease in looking
365 time, and an increase in number of shifts during the previous trial’s stimulus presentation, as

³ It should be noted that a suggested, minimal sample of 100 observations for this statistic was not met and should therefore only be taken as an indication rather than a statistical test (Cross & Jain, 1982).

⁴Compared to k-means clustering, this method is more robust against outliers and allows better interpretation of the emerging clusters (Kaufman & Rousseeuw, 2009). However, we ran another analysis using k-means with a comparable pattern of results.

366 well as increased trigger time for the current trial (as an indication of a switch-cost; Daw et al.,
367 2006; Hayden et al., 2011) would predict an exploratory switch. A Bayesian hierarchical
368 binomial regression model was fitted using the ‘brms’ package (Bürkner, 2017), with the three
369 predictors as population-level (“fixed”) effects and trial-by-trial trigger decisions (stay = 0,
370 switch = 1) as the outcome variable. Furthermore, we included random intercepts at the
371 individual level to reflect the structure of the data.

372 2.5.3.2 *Stimulus-dependent switch-prediction.* We hypothesised that characteristics of
373 the presented stimuli would affect the likelihood to switch. For instance, experiencing two
374 highly similar stimuli right after one another offers little new information about the category
375 and could lead to disengagement in favour of another information source. Consequently, we
376 would expect greater similarities (as judged by participants in the online rating study) between
377 successive stimuli to predict a subsequent switch. Furthermore, this effect may moderate the
378 behavioural indicators above, so that the same model was used, to which the stimulus
379 similarities interactions were added to capture the full complexity of the task. As this measure
380 required runs of minimum length 2, any single-trial runs and first trials of each run were
381 excluded from this analysis. Thus, we kept these two models separate as they capture the
382 exploration choices to different degrees.

383 2.5.3.3 *Differences between clusters.* If our data showed evidence of clustering with
384 regard to how infants engaged with the paradigm, we would further explore whether the
385 predictors above differed between the emerging clusters. Thus, we would include clusters as
386 interaction effects in both models.

387 **3. Results**

388 Where possible, both frequentist p-values and Bayes factors (via JASP 0.16.2.0) will
389 be reported. However, we chose to fit Bayesian models for the switch-predictions as they
390 provide effect distributions rather than point estimates which were considered more appropriate

391 for the inherently exploratory nature of a study employing a novel paradigm. Additional graphs
392 for model fit comparisons can be found in the supplementary materials (S1.1). Data and
393 analysis code are available on the OSF at:

394 https://osf.io/ayjv7/?view_only=0574096344c041b4a8d0fa493a1d94d2

395

396 **3.1 Infants explored non-randomly**

397 First, we investigated whether infants' exploration patterns showed any systematicity
398 different from chance. Kolmogorov-Smirnoff tests for two samples indicated for both
399 variables, switch-proportion ($D = 0.63, p < .001$) and category entropy ($D = 0.58, p < .001$),
400 that the simulated (random) and observed data did not come from the same distribution
401 (supplementary materials Figure S1). More specifically, infants showed a general exploitative
402 tendency as the average switch-proportion was significantly lower than 50% ($M = .28, SD =$
403 $.28$, Wilcoxon signed-rank test against 0.5: $W = 362.00, p < .001; r_c = -0.67; BF_{10} = 279.35$).
404 There was no systematic bias for triggering either a specific category ($W = 850.00, p = .205, r_c$
405 $= -0.18, BF_{10} = 0.32$) or side ($W = 1214.00, p = .245, r_c = 0.16, BF_{10} = 0.20$).

406 **3.2 Three exploration patterns**

407 Number of triggers, switch-proportion, and category entropy were chosen prior to
408 inspecting the data as a means to characterise different aspects of the infant-generated
409 exploration sequences. We explored their relations via Kendall rank correlations due to non-
410 normality and ties in the data. Across the whole sample, number of triggers moderately
411 negatively correlated with switch-proportion ($r_\tau = -.27, p = .002$) and category entropy ($r_\tau = -$
412 $.18, p = .044$), whereas switch-proportion and category entropy were strongly positively
413 correlated ($r_\tau = .56, p < .001$). However, examining the distribution of exploration triggers
414 (Figure 2) showed that a group of 10 participants engaged in the study only very briefly, making
415 both switch-proportion and category entropy less informative. When removing this sub-

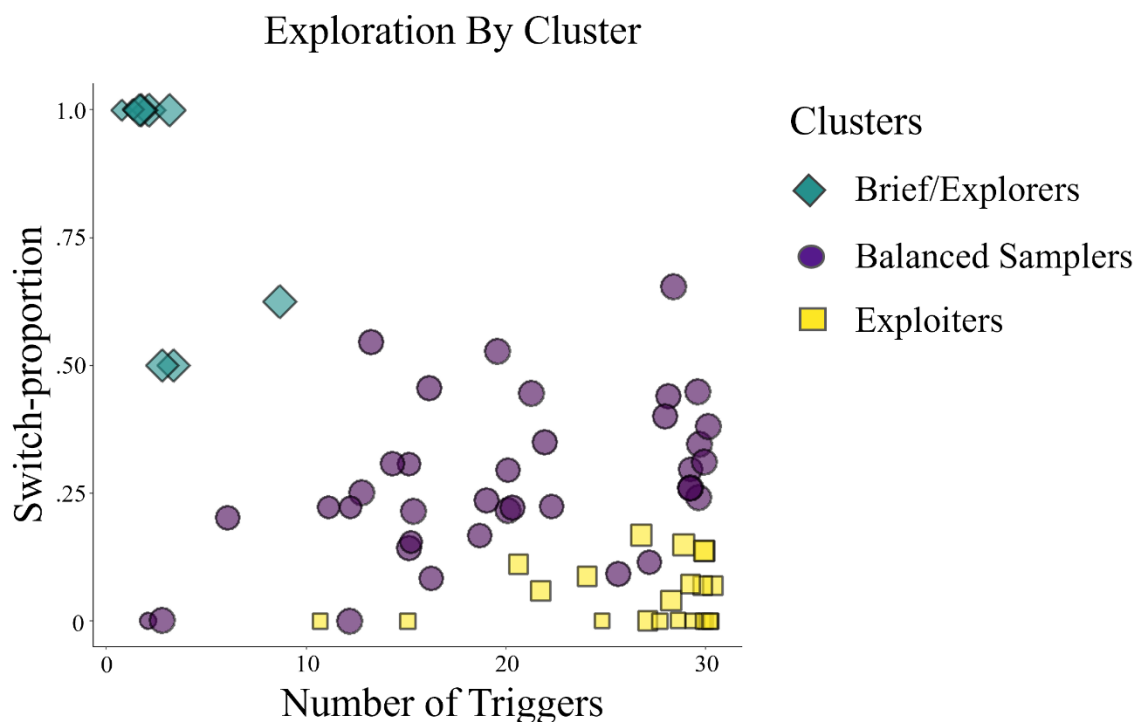
416 sample, the number of triggers were no longer related to either switch-proportion ($r_{\tau} = -.13$, p
417 $= .166$) nor category entropy ($r_{\tau} = -.14$, $p = .150$), while the relation between these latter two
418 variables increased even further ($r_{\tau} = .63$, $p < .001$). Thus, these variables appear to largely
419 overlap in the variance they explain, possibly due to having only two triggerable information
420 sources.

421 Visualisation of the average silhouette (that is, minimising within-cluster dissimilarities
422 while maximising between-cluster dissimilarities; Rousseeuw, 1987) and within-cluster sums
423 of squares statistics suggested the optimal number of clusters to be three. The three emerging
424 clusters (Figure 2) describe very brief, medium long, and very long sequences with additional
425 variations in switch-proportion and category entropy (Table 1). Especially the sequences of
426 more than 10 triggers could be differentiated by the extent to which the infant switched between
427 and sampled from both categories. As, however, the very short sequences did often sample
428 both categories, we decided to characterise the clusters as *brief explorative* ($n = 9$), *long*
429 *exploitative* ($n = 22$), and *more balanced* ($n = 37$) sampling sequences (from here on referred
430 to more accessibly as *brief/explorers*, *exploiters*, and *balanced samplers*, however, not
431 implying stable individual differences).

432 While balanced samplers tended to explore and exploit both available information
433 sources by sampling from both categories, the other two clusters captured behavioural patterns
434 towards the opposite ends of the explore-exploit spectrum: *brief/explorers* engaged only very
435 briefly, often discovered both information sources but lacked exploitation, whereas *exploiters*
436 recorded on average the longest overall engagement, switched the least and focused most of
437 their triggers towards one category, thereby lacking exploration.

438 **Figure 2**

439 *Exploratory Clusters based on behavioural characteristics*



440

441 *Note.* Emerging exploration clusters based on overall engagement (number of triggers),
 442 exploitative tendencies (switch-proportion) and sampling systematicity (category entropy,
 443 reflected in point size with larger shapes indicating larger entropy values and thus, less
 444 predictable structures).

445

446 While a sub-sample of participants ($n = 8$) triggered only one side throughout the
 447 experiment, the remaining $n = 60$ did record triggers towards both sides. Interestingly, $n = 2$ of
 448 the *exploiters* triggered only one side during warm-up but then only the respective other side
 449 during the exploration phase, lending support to the notion that repeated triggering was not
 450 necessarily due to a persistent side preference established during the warm-up phase.
 451 Furthermore, we found that on average, explorers took the longest to make a trigger and
 452 exploiters the shortest (Table 1), supported by a negative Spearman correlation between mean

453 trigger time and overall engagement ($r = -.38, p = .001$). While infants in all three clusters
 454 looked similarly long at the triggered stimuli (which did not correlate with any of the
 455 exploration variables), higher rates of gaze-shifting were positively related to higher rates of
 456 switching ($r = .38, p = .001$) and category entropy meaning triggers towards both categories (r
 457 $= .27, p = .024$). It should be noted, however, that gaze-shifting did not occur during most
 458 stimulus presentations and thus, does not imply overall random or erratic looking behaviour
 459 (full correlation matrix of exploration and looking variables in supplementary materials).

460

461 **Table 1.** Descriptive statistics per cluster. Means (standard deviations) for each of the
 462 characterising variables.

463

	Brief/Explorers	Balanced	Exploiters
N	9	37	22
Sex (m:f)	6:3	19:18	9:13
Age (in months)	11.0 (0.49)	11.2 (0.56)	11.1 (0.57)
Warm-up trials	2.33 (1.32)	3.54 (1.57)	3.95 (1.50)
Overall Engagement	2.89 (2.42)	19.90 (8.02)	26.50 (5.16)
Switch-proportion	0.89 (0.17)	0.27 (0.15)	0.05 (0.06)
Category entropy	0.75 (0.43)	0.76 (0.22)	0.17 (0.18)
Trigger time (ms)	2435 (1782)	2094 (867)	1561 (451)
Looking time (ms)	2892 (506)	2856 (567)	2867 (890)
Gaze-shifts (per trial)	.51 (.40)	.51 (.29)	.36 (.38)

464

465 Multinomial regressions revealed that cluster membership was independent of age and sex, as
466 neither predictor reached significance (all $ps > .05$), although there seemed to be a slight
467 tendency for the *briefexplorers* to be males and *exploiters* to be females.

468

469 **3.3 Trial-by-trial trigger decisions were associated with behavioural and stimulus-** 470 **dependent predictors**

471 We fitted Bayesian hierarchical binomial regression models to investigate the
472 associations between behavioural and stimulus-dependent indicators of learning progress and
473 the likelihood of making an exploratory switch. The behavioural models included 1176
474 observations, whereas the stimulus-dependent models included 862 observations. In both
475 cases, we specified a Bernoulli family likelihood (as we focus on each trial instead of an
476 individual's distribution of switch events) and a weakly informative prior [normal(0,2)] across
477 beta parameters. This allowed for possibility effect sizes between -4 and 4. All models fitted
478 successfully with sufficient numbers of samples, stationary, well-mixing chains, all rhats at
479 1.00, and credible posterior predictive checks. Model fit comparisons (see supplementary
480 materials for more details) found that both behavioural (3.1) and stimulus-dependent (3.2)
481 models improved fit compared to their respective intercept models. Adding the cluster
482 interactions (3.3) explained additional variance but did not greatly improve model fit.

483 Figures 3 to 5 illustrate the estimated effect sizes as probability distributions, with
484 values further away from zero indicating stronger associations between predictors and outcome
485 variable. If the distribution's mass is below zero the effect of the predictor on the outcome is
486 negative, and if its mass is above zero the effect is positive. A distribution centred on zero
487 indicates that predictor and outcome are not associated.

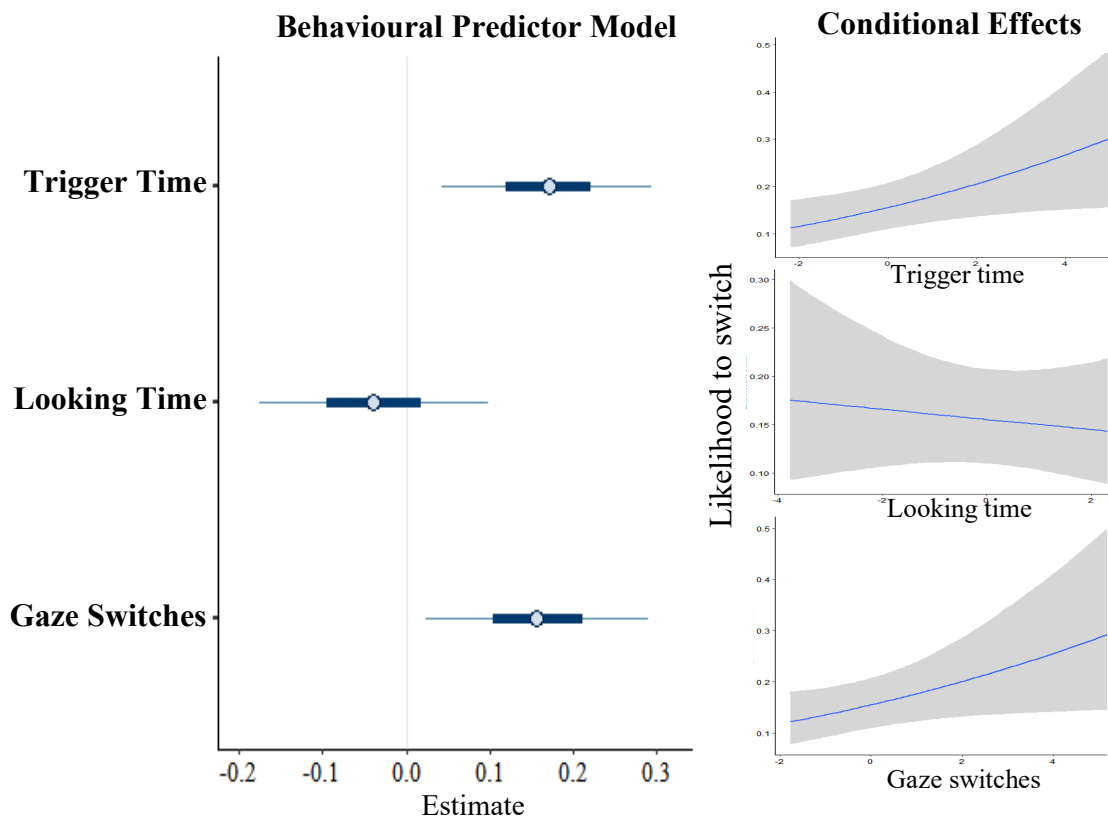
488 **3.3.1 Switches were predicted by behavioural measures.** The first model investigated
489 the associations between behavioural predictors and the trial-by-trial likelihood to switch to the

490 other category. It showed that the effects were in line with our expectations (Fig. 3): there was
491 a positive association between *trigger time* and the likelihood to switch as the variable's
492 distribution's mass was above zero (estimated mean effect $\hat{b} = 0.17$, 95%-Credible
493 Interval(CI)[0.02; 0.32]). Thus, longer times to trigger one of the houses indicated that this
494 trigger would likely be a switch to the other category. Furthermore, there was a marginally
495 negative association between *looking time* and the likelihood to switch ($\hat{b} = -0.04$, 95%-CI[-
496 0.20; 0.13]), indicating a trend for an association between decreased looking time at the
497 presented stimulus and an increased likelihood of switching to the other category on the
498 following trial. Lastly, there was a positive association between *gaze-shifts* and the likelihood
499 to switch, as most of its distribution's mass was above zero ($\hat{b} = 0.16$, 95%-CI[0.00; 0.31]).
500 This suggests that increased gaze-shifting towards the other, not currently triggered side
501 predicted switching towards that side on the next trial.

502

503 **Figure 3**

504 *Behavioural Predictors for Switching*



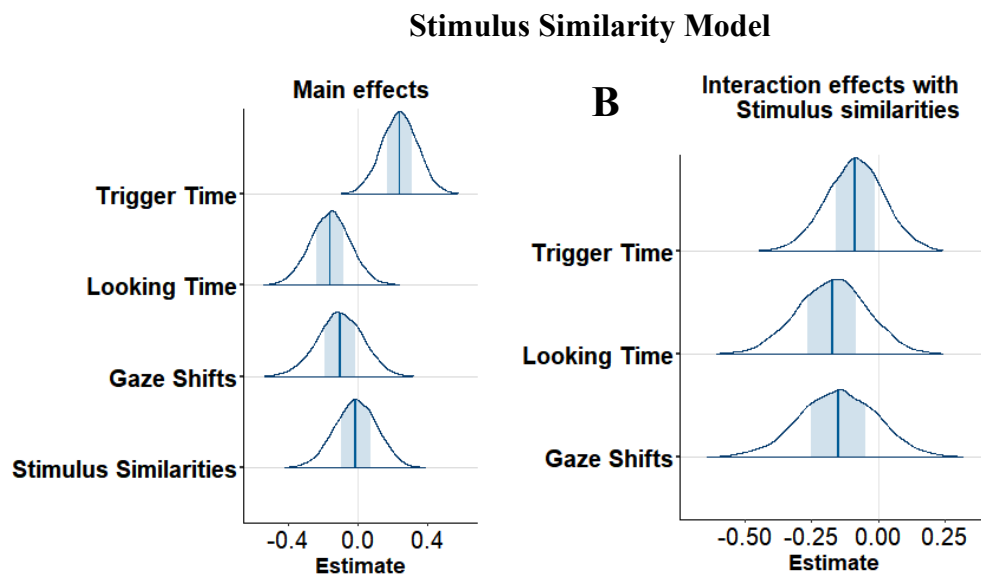
505 *Note.* **Left:** probability distributions of effects for each of the behavioural predictors (mean,
 506 50% probability interval, and 95%CI). **Right:** Conditional effects of each predictor on the
 507 likelihood to make an exploratory switch.

508

509 **3.3.2 Stimulus similarities interacted with behavioural predictors.** This model
 510 investigated whether infants' exploratory decisions were sensitive to environmental measures
 511 of learning progress as indicated by the similarities between consecutively observed stimuli
 512 (Fig. 4).

513 **Figure 4**

514 *Interactions between Stimulus Properties and Behavioural Markers*



515 *Note.* Main effects (A) and interactions (B) of the predictors on the likelihood to switch.

516 A: Probability distributions for each main effect of the predictors on the outcome variable,
 517 including stimulus similarities. B: Probability distributions for each interaction effect between
 518 the stimulus similarities and each predictor. The dark, vertical line indicates the estimate's
 519 mean, the shaded area surrounding the mean represents the 50% probability interval, and the
 520 distributions' tails cover the 99% probability interval.

521

522 Both effects for *trigger time* (positive) and *looking time* (negative) were consistent with
 523 the previous model's findings (trigger time: $\hat{b} = 0.24$, 95%-CI[0.04; 0.44]; looking time: $\hat{b} =$
 524 -0.16 , 95%-CI[-0.39; 0.07]), albeit strengthened, as their mean estimates were now further
 525 away from zero. However, the *gaze-shift* effect was now marginally negative (compared to
 526 positive at 3.1), meaning that, after reduction of observations and controlling for stimulus
 527 similarities, fewer gaze shifts were associated with a higher likelihood to switch ($\hat{b} = -0.10$,
 528 95%-CI[-0.37; 0.15]). *Stimulus similarities* as a main effect had the smallest direct, negative,

529 association with the likelihood to switch, where the probability distribution is almost centred
530 on zero ($\hat{b} = -0.01$, 95%-CI[-0.26; 0.23]).

531 With regards to interactions (Fig. 4B), all three effects were found to be negative and
532 of similar strength. As the interaction effect for *trigger time* was of opposite polarity to its main
533 effect, this indicated a weakening of the main effect for higher similarity (slopes became less
534 steep). In contrast, interactions were of the same polarity (negative) as the main effects for
535 *looking time* and *gaze-shift*, indicating a strengthening of those effects for higher stimulus
536 similarities (slopes became steeper). In practice, this can be interpreted, that after seeing two
537 very similar stimuli, it took comparatively less time to make a switch ($\hat{b} = -0.09$, 95%-CI[-
538 0.30; 0.13]), possibly suggesting a reduction in switch cost (compare Daw et al., 2006; Hayden
539 et al., 2011). Then, even smaller decreases in looking time ($\hat{b} = -0.17$, 95%-CI[-0.43; 0.08])
540 and fewer gaze-shifts ($\hat{b} = -0.15$, 95%-CI[-0.45; 0.14]) were associated with a higher
541 likelihood to switch. Overall, these findings indicate that infants showed some sensitivity
542 towards similarities between consecutively presented stimuli, in the sense that they interacted
543 with their engagement behaviour.

544 **3.3.3 Cluster interactions: pulling effects apart.** As the cluster analysis found three
545 clusters of exploratory patterns – capturing brief explorative, long exploitative, and more
546 balanced sampling – we wanted to investigate whether the previously found associations
547 between behavioural and stimulus-dependent indicators would differ between the clusters.
548 Thus, we included interaction effects in both models and also looked at the balanced samplers
549 in isolation (see supplementary materials S.12 and S.13).

550 We found that *behaviourally*, adding cluster interactions could explain additional
551 variance making the looking time effect more pronounced ($\hat{b} = -0.10$, 95%-CI[-0.28; 0.09])
552 which seemed to be mainly driven by the balanced samplers as the interaction indicated weaker
553 effects for exploiters (opposite polarity: $\hat{b} = 0.48$, 95%-CI[0.02; 0.25]; Figure S3 in

554 supplementary materials). Contrastingly, the positive effects of trigger time ($\hat{b} = 0.13$, 95%-
555 CI[-0.04; 0.09]) and gaze-shifts ($\hat{b} = 0.05$, 95%-CI[-0.13; 0.09]) were stronger for the
556 exploiters than balanced samplers (same polarity for trigger time: $\hat{b} = 0.14$, 95%-CI[-0.23;
557 0.19] and gaze-shifting: $\hat{b} = 0.43$, 95%-CI[0.06; 0.19]). Effects were overall weaker for the
558 group of explorers due to low numbers of observations.

559 Further analyses showed that stimulus-similarity interactions were also mainly driven
560 by balanced samplers where we found very similar patterns of the predictors (looking time: \hat{b}
561 = -0.18, 95%-CI[-0.43; 0.06]); trigger-time: $\hat{b} = 0.18$, 95%-CI[-0.05; 0.12]; gaze-shifts: $\hat{b} =$
562 -0.10, 95%-CI[-0.37; 0.14]; similarity: $\hat{b} = -0.05$, 95%-CI[-0.31; 0.13]), with stimulus
563 interactions strengthening the looking time effect for balanced samplers ($\hat{b} = -0.18$, 95%-CI[-
564 0.47; 0.15]) but marginally weakening it for exploiters ($\hat{b} = 0.02$, 95%-CI[-0.63; 0.34]).
565 Conversely, stimulus interactions weakened the trigger time effect for balanced samplers (\hat{b}
566 = -0.14, 95%-CI[-0.39; 0.13]) but strengthened it for exploiters ($\hat{b} = 0.19$, 95%-CI[-0.31;
567 0.26]) but with larger margins (see supplementary materials S1.2 & S1.3 for more details and
568 additional figures).

569

570 **4. Discussion**

571 We present a powerful new paradigm enabling infants' active exploration within an
572 otherwise controlled environment. Infants triggered the presentation of exemplars from two
573 novel categories via their fixations on screen, allowing them to generate their own sampling
574 sequences. We found a general exploitative tendency with most infants more likely to make
575 consecutive triggers towards the currently sampled information source, representing a
576 category, than to switch to the other. Furthermore, self-generated sequences clustered into three
577 sampling patterns, characterised by length of engagement and balance between exploration and
578 exploitation of either category. The largest emerging group of infants sampled information

579 from both categories in a more balanced way than the other two, who respectively presented
580 shorter, more explorative tendencies (lacking exploitation of either category and with little
581 engagement with the study overall), and longer, more exploitative tendencies (lacking
582 exploration of the alternative category). Importantly, infants' pre-switch engagement
583 behaviour (longer trigger time, less looking, and more gaze-shifting) was associated with
584 infants' increased likelihood to make an exploratory switch at the next trial and interacted with
585 experienced stimulus similarities.

586 The overall exploitative tendency to consecutively sample from one information source
587 is crucial for knowledge acquisition especially early in development (e.g., Smith et al., 2018)
588 and can be compared to a familiarity preference leading to full encoding of the encountered
589 information (e.g., Rose et al., 1982). Indeed, more naturalistic studies have found similar
590 exploitative tendencies in the way infants engage with objects in their daily lives (Bambach et
591 al., 2018; Smith et al., 2018) and how they structure their engagement with novel toys during
592 free play (Karmazyn-Raz & Smith, 2023). Due to their developing memory capacities, infants
593 may be especially prone to exploiting information, while its reduction across development
594 could be attributed to exploration becoming more flexible and efficient (Meder et al., 2021;
595 Pelz & Kidd, 2020; Ruggeri et al., 2016).

596 Furthermore, we observed that infant-generated sequences grouped into three clusters
597 capturing brief explorative, long exploitative, and more balanced sampling, the latter being
598 characterised by exploration and exploitation of both categories. Note that the labels were
599 chosen with the explicit aim to describe the clusters on one key dimension - between
600 exploration and exploitation. Although some of the sequences were very short, it was notable
601 that in these short sequences infants often switched between categories instead of repeatedly
602 sampling the same category, so that these brief sequences are better described as explorative
603 than exploitative. However, more conservative approaches may have excluded infants with few

604 triggers, in which case the more *balanced* sequences would have been called explorative,
605 instead.

606 While the *brief/explorers* may not have been curious enough about revealing the
607 exemplars in the two houses, or possibly found the setting too unfamiliar and thus only engaged
608 shortly, they nevertheless tended to discover both categories but did not exploit their
609 information potential by creating longer within-category runs. In contrast, *exploiters* engaged
610 the longest but mainly focused on one category and thus missed the opportunity to explore and
611 exploit the second category's information potential. While 36% of *exploiters* did stick to one
612 side throughout the experiment, the remaining 64% also discovered the other side as an
613 information source but did not exploit its potential. This could either indicate a prevailing
614 familiarity preference with which the discovery of the other, unfamiliar category could not
615 compete, or a preferential engagement with the same, repeated motor behaviour.

616 However, in studies with toddlers (14-30 months of age) on manual exploration of
617 objects from different categories, Mandler and colleagues (1987, 1991) found similar patterns,
618 characterised as either exhaustive categorisers who, similar to our *balanced samplers*,
619 generated runs of touching exemplars from one or the other category in turn, single categorisers
620 who focused on one category, similar to our *exploiters*, or non-categorisers who did not
621 systematically engage with either category, similar to our *brief/explorers*. Thus, our results
622 present converging evidence with these findings, indicating that similar exploratory patterns
623 can be found across age groups and exploration modalities. Although group membership in our
624 study was not significantly related to age or sex, these exploration patterns may be associated
625 with aspects of cognitive development such as processing speed (manifesting in habituation
626 paradigms: Cao et al., 2023; Feldman & Mayes, 1999), cognitive control (Munakata et al.,
627 2012; Pelz et al., 2015), or personality traits such as temperament (Rothbart, 2007; van den
628 Boom, 1994). Yet, the current paper makes no assumptions of these patterns directly reflecting

629 stable individual differences as no test-retest reliability or comparative behaviour was assessed.
630 Future work will address these questions.

631 Lastly, we found that infants' engagement behaviour in interaction with stimulus
632 similarities (but not smaller or larger similarities directly; compare Twomey & Westermann,
633 2018) was associated with their likelihood to re-engage or make an exploratory switch. This
634 indicates that it is not only the information the environment offers that predicts disengagement
635 (Kidd et al., 2012; Poli et al., 2020) but also to what degree the agent engages with said
636 information. For instance, longer looking was predictive of re-engagement with the current
637 information source as would be expected from habituation paradigms and familiarity
638 preferences, indicating that the infant still has more information to encode (e.g., Rose et al.,
639 1982). Conversely, infants were more likely to make a switch on the following trial after
640 looking less at the presented stimulus, and especially so if it was visually highly similar to the
641 previously encountered exemplar, thus, not offering additional information about the category.
642 This looking time effect was most pronounced for the cluster of *balanced samplers*, which may
643 indicate that their behaviour was most in line with the mentioned habituation paradigms and
644 theoretical assumptions made by the explore-exploit framework if the engagement is mainly
645 driven by the sampled and encoded information.

646 In contrast, the other clusters may have been more affected by dynamics such as the
647 cognitive switch cost attributed to inhibiting repeated sampling behaviour and redirecting one's
648 attention (Daw et al., 2006; Hayden et al., 2011; Pelz et al., 2015). This cost was observed here
649 as the trigger time effect with longer durations predicting a switch and was most pronounced
650 in the cluster of *exploiters*, suggesting that if they did manage to inhibit their exploitative
651 tendency, they were very likely to make a switch. Lastly, we observed that, before making a
652 switch at the next trial, infants shifted their gaze more towards the non-triggered side during
653 stimulus presentation. This effect, however, disappeared when including the stimulus

654 similarities. Due to the nature of consequently excluded observations (e.g., switch trials), this
655 may indicate that infants were especially likely to shift their gaze in a comparative manner after
656 making a switch (Kovack-Lesh et al., 2008; Oakes et al., 2009) and then returned to the
657 previously triggered category.

658 Together these findings are also in line with assumptions of the learning progress
659 hypothesis (Altmann et al., 2021; Oudeyer et al., 2007; Poli et al., 2024; Twomey &
660 Westermann, 2018) while offering exciting new insights into the systematicity of infants'
661 exploration history guiding their active sampling behaviour previously only shown for
662 engagement in fully structured infant studies (e.g., Poli et al., 2020).

663 **4.1 Methodological Considerations**

664 The three variables characterising different aspects of the exploration sequences were
665 chosen prior to inspecting the data. We found, however, that in this paradigm with only two
666 options, switch proportion and category entropy were highly correlated and thus explained very
667 similar variance in the data. Future studies with two options might consider only including
668 switch proportion whereas all three might be more informative for paradigms with multiple
669 sampling options.

670 Twenty-nine per cent of infants in this study fell into the cluster of *exploiters*, who
671 triggered mostly or even exclusively one of the two novel categories. As suggested, this
672 behaviour may either be indicative of a prevailing familiarity preference or a lack of cognitive
673 control to overcome the cost of disengaging from a repeated behaviour and could be a remnant
674 of the developmental phenomenon of low-level, visual stickiness (Colombo, 2001; Kulke et
675 al., 2015; Wass & Smith, 2014). Such stickiness itself should, however, disappear by about
676 nine months of age (e.g., Wass & Smith, 2014) and would, by definition, be interrupted here
677 by the central, gaze-contingent attention-getter. Thus, rather than continued staring,

678 exploitation of a category required active re-engagement at each trial, making the other
679 explanations more likely.

680 While we aimed to keep the warm-up phase as unstructured as possible to truly gauge
681 infants' self-guided exploration, future studies may want to include controls ensuring at least
682 three warm-up triggers to realise the mechanism (Wang et al., 2012), as well as at least one
683 trigger towards all gaze-contingent areas on the screen. This could avoid the possibility that
684 some infants remain ignorant of other potential information sources they could engage with.
685 Nevertheless, by enhancing ecological validity but also accepting the thereby increased
686 variance in the data, our study provides important insights into infants' active sampling
687 behaviours reflecting that exploration is also a skill and might require initial guidance (Matas
688 et al., 1978; McQuillan et al., 2020; Vygotsky & Cole, 1978).

689 The stimuli being complex visual categories did not allow us to compute trial-based
690 learning progress in a more straightforward way as was possible in previous studies
691 investigating improvements in anticipation of a target's location (Poli et al., 2020, 2022).
692 Nevertheless, we were able to show convergent evidence for the association between infants'
693 engagement behaviour and information sampling behaviour in interaction with the experienced
694 stimulus characteristics as proximal indicators of learning progress. Future studies could seek
695 to gather differentiating insights into predominantly environmental exploration (e.g., number
696 of/cost associated with interactive information sources; Wang et al., 2012; Bazhydai et al.,
697 2022) compared to predominantly information-based exploration (e.g., manipulating stimulus
698 similarities or reward value; Tummeltshammer et al., 2014).

699 **4.2 Conclusion**

700 In this study, 10-12-month-old infants self-generated exploration sequences within the
701 novel Curious Choices paradigm. This allowed us to gather new insights into both, general
702 patterns of curiosity-driven exploration in infants, e.g., exploitative tendencies, but also the

703 mechanisms underlying such dynamic behaviour. Importantly, for the first time, we showed
704 that moment-to-moment sampling choices were not spontaneous but associated with the
705 infant's preceding engagement behaviour modulated by the information offered from the
706 presented stimuli. However, we also observed a large variance within infants' curiosity-based
707 information sampling which may be constrained by their developing exploration skills. A
708 remaining question is whether the observed exploration tendencies are stable and related to
709 other aspects of development, which we are currently investigating. Together, we offer new
710 methodological avenues for future research into infants' active exploration and present novel
711 insights converging with and expanding the current literature regarding this crucial aspect of
712 human development.

713

714 **Author contributions**

715 **Elena Altmann:** Conceptualisation; Data curation; Formal analysis; Investigation;
716 Methodology; Project administration; Software; Visualisation; Writing - original draft; and
717 Writing - review & editing. **Marina Bazhydai:** Conceptualisation; Methodology; Supervision;
718 Writing - review & editing. **Gert Westermann:** Conceptualisation; Funding acquisition;
719 Methodology; Supervision; Writing - review & editing.

720

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727 Running head: CURIOUS CHOICES

728

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1020 **Supplementary materials**

1021

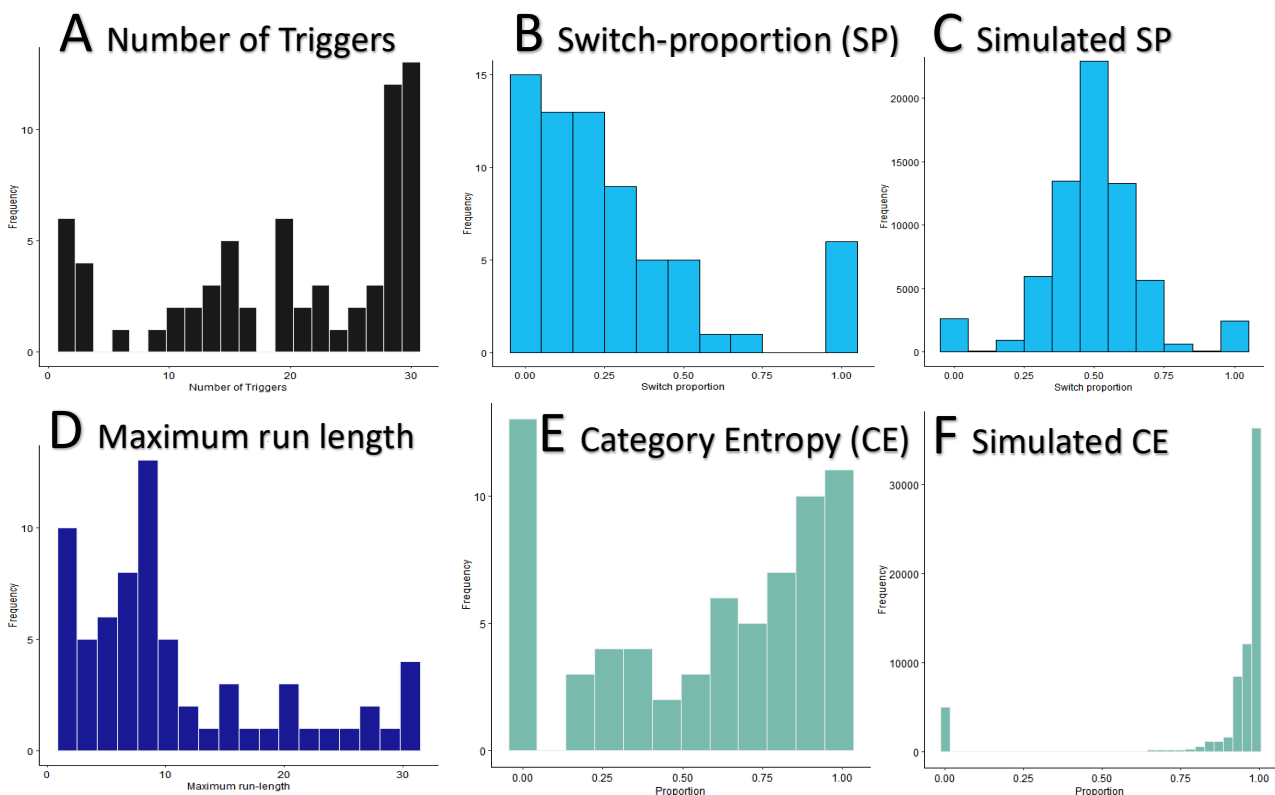
1022 These supplementary materials are made up of two parts. The first part (S1) provides
 1023 additional detail about reported results, whereas the second part (S2) reports the additional
 1024 adult study based on which stimulus similarities were computed. Data and analysis code for all
 1025 results are available on the OSF at:

1026 https://osf.io/ayjv7/?view_only=0574096344c041b4a8d0fa493a1d94d2

1027

1028 **Figure S1**

1029 *Distributions of observed and simulated exploration variables*



1030 *Note.* Exploratory aggregates to describe the sample’s behaviours.

1031 **A:** Overall engagement as illustrated by the distribution of triggers across participants **B:**
 1032 Exploitative tendencies as indicated by majority of switch-proportions being below 50%
 1033 (vertical line), **C:** Simulated switch-proportions based on a chance mechanism (1000 draws per

1034 participant based on their number of triggers) **D**: Distribution of longest continuous runs
 1035 (consecutively triggering the same category) per participant, **E**: Category entropies across
 1036 participants, where higher values indicate more similar number of triggers towards both
 1037 categories and the minimum of 0 indicates that all triggers were towards only one category,
 1038 and **F**: Simulated category entropies based on a chance mechanism.
 1039

Table S1. Correlations between exploration and looking variables.

	Overall Engagement	Switch Proportion	Category Entropy
Mean Trigger Time	-.38 ($p = .001$)	.10 ($p = .411$)	.22 ($p = .072$)
Mean Looking Time	.06 ($p = .653$)	-.12 ($p = .319$)	-.11 ($p = .359$)
Mean Gaze-shifts	-.01 ($p = .915$)	.38 ($p = .001$)	.27 ($p = .024$)

1040

1041 **S1 Trial-by-trial trigger decision predictions**

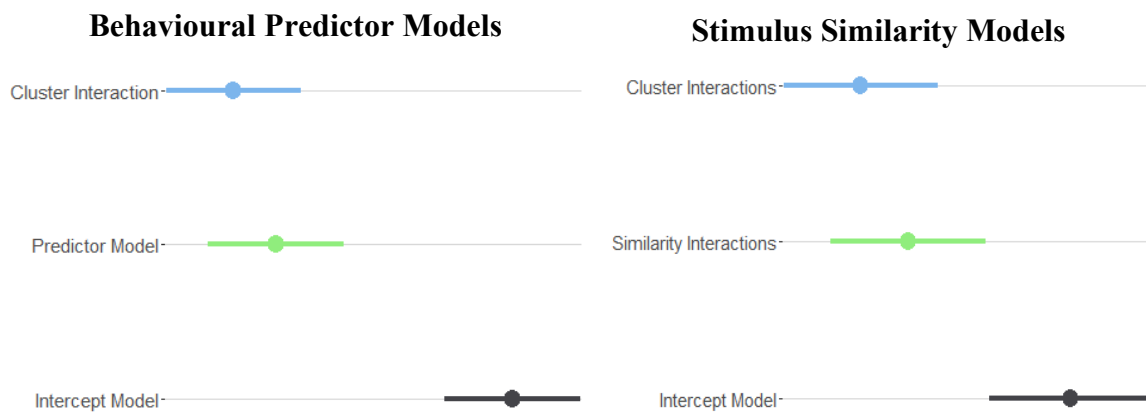
1042 **S1.1 Model comparisons**

1043 ***S1.1.1 Behavioural Models.*** Model fit comparison based on the leave-one-out cross
 1044 validation values (loaic) measure (Fig. S2, left) showed that the main model greatly improved
 1045 the fit compared to the intercept model as its loaic value is substantially smaller and standard
 1046 errors are not overlapping. Adding the interaction terms for clusters did improve the fit further,
 1047 however, the standard errors are widely overlapping suggesting that the added complexity may
 1048 not be worth the fit improvement.

1049

1050 **Figure S2**

1051 *Model Comparisons*



1052

1053 *Note.* Model comparisons based on the leave-one-out cross validation (looic) values on the x-
 1054 axis. Smaller looic values suggest better fit. Standard errors are indicated.

1055 Left: Behavioural models (with reference to 3.1 and 3.3). Right: Stimulus-dependent models
 1056 (with reference to 3.2).

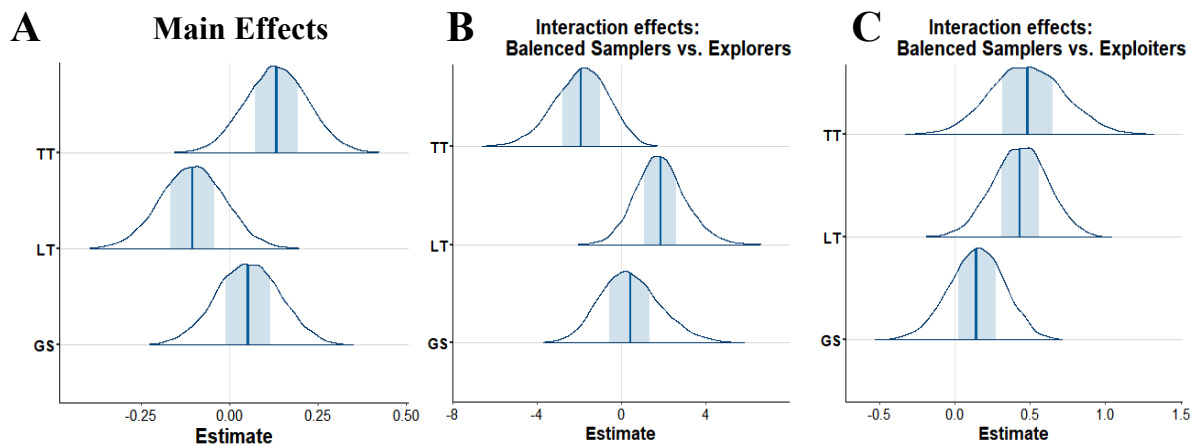
1057

1058 ***S1.1.2 Stimulus-dependent Models.*** Model fit comparison based on the looic measure
 1059 (Fig. S2, right) showed that the main model improved the fit compared to the intercept model
 1060 as its looic value is substantially smaller and standard errors are not overlapping. Adding the
 1061 interaction terms for clusters did improve the fit further, however, the standard errors are
 1062 widely overlapping suggesting that the added complexity may not be worth the fit
 1063 improvement.

1064

1065 **Figure S3**

1066 \Behavioural switch prediction between Clusters \



1067 Note. Probability distributions for each of the behavioural predictors on the outcome variable.

1068 A: main effects. B: Interaction effects comparing the *balanced samplers* to the *explorers*. C:

1069 Interaction effects comparing the *balanced samplers* to the *exploiters*.

1070 If the interaction effect is of the same polarity as the main effect (e.g., both negative), it

1071 indicates a strengthening of that effect in the comparative group (slopes become steeper). If the

1072 interaction effect is of opposing polarity, the effect is weaker in the comparative group (slopes

1073 become less steep).

1074

1075 S1.2 Three-way interactions

1076 In more detail, the main effects are still the same in polarity and look mostly like the

1077 main model (Fig. S4A). The three stimulus similarity interaction effects reported above have

1078 strengthened with slightly more negative values (Fig. S4B). The 3-way-interactions then

1079 indicate to what degree these interaction effects differ between clusters (Figures S4C, S4D). If

1080 the terms have the same polarity, the comparison cluster seems to have a stronger effect,

1081 whereas opposite polarities suggest a weaker interaction effect for that cluster. Regarding

1082 looking time, interaction terms for both explorers and exploiters are centred around zero

1083 indicating that there are no differences between clusters in the way that stimulus similarities

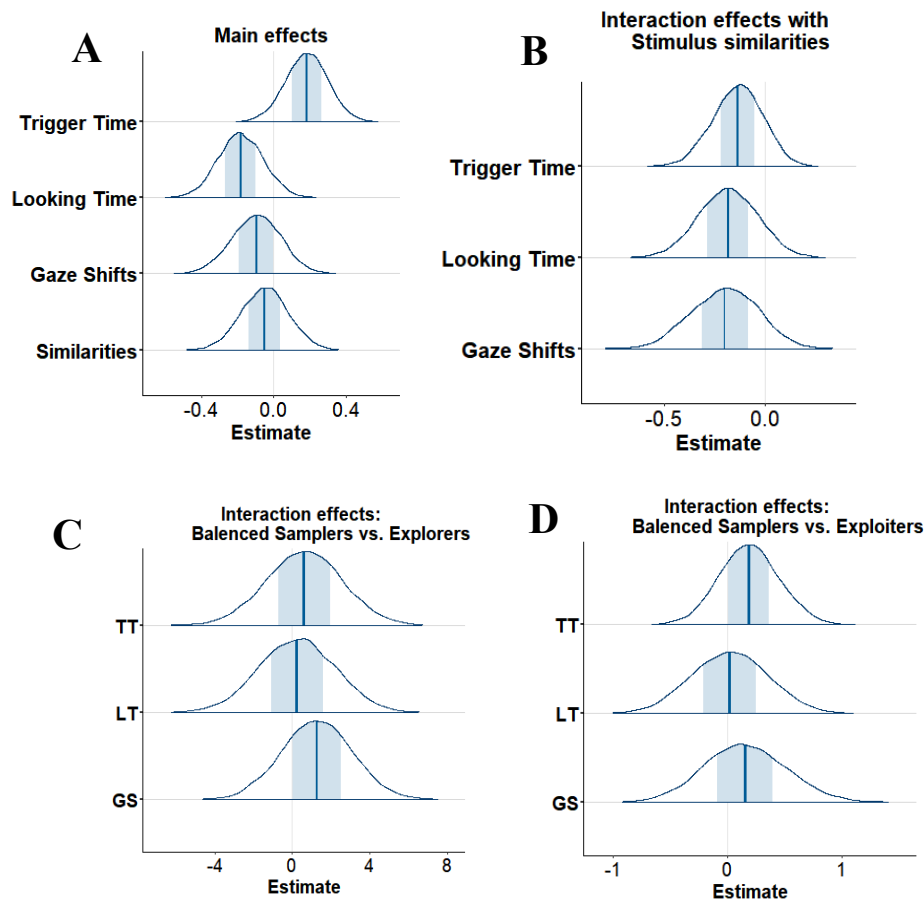
1084 affect looking time and in turn the likelihood to switch. In contrast, the interaction effects for

1085 the other two predictors are positive across clusters indicating that there are differences
1086 between the clusters. As noted above, the simple interactions are all negative which means they
1087 are of opposing polarity to these 3-way-interactions. This indicates that both, the effect of
1088 stimulus similarity on trigger time and on gaze-shifts is weaker for explorers and exploiters
1089 compared to the balanced samplers. This suggests that the main effects and interaction effects
1090 may be stronger if we had only looked at the balanced samplers.

1091

1092 **Figure S4**

1093 *Effects for 3-way interaction model*



1094 *Note.* Probability distributions for each of the behavioural predictors on the outcome variable.

1095 A: main effects of the behavioural predictors on likelihood to switch. B: Simple interaction

1096 effects of stimulus similarities on the behavioural predictors. C: 3-way-interaction comparing

1097 how similarity interaction effects differ between *explorers* compared to *balanced samplers*. D:

1098 3-way-interaction comparing how similarity interaction effects differ between *exploiters*

1099 compared to *balanced samplers*. Note the scale difference for the *explorer* plot, which is likely

1100 due to the limited number of observations in the cluster of explorers.

1101 **S1.3 Balanced samplers in isolation**

1102 As the 3-way interactions suggested that the effects were mostly driven by the balanced

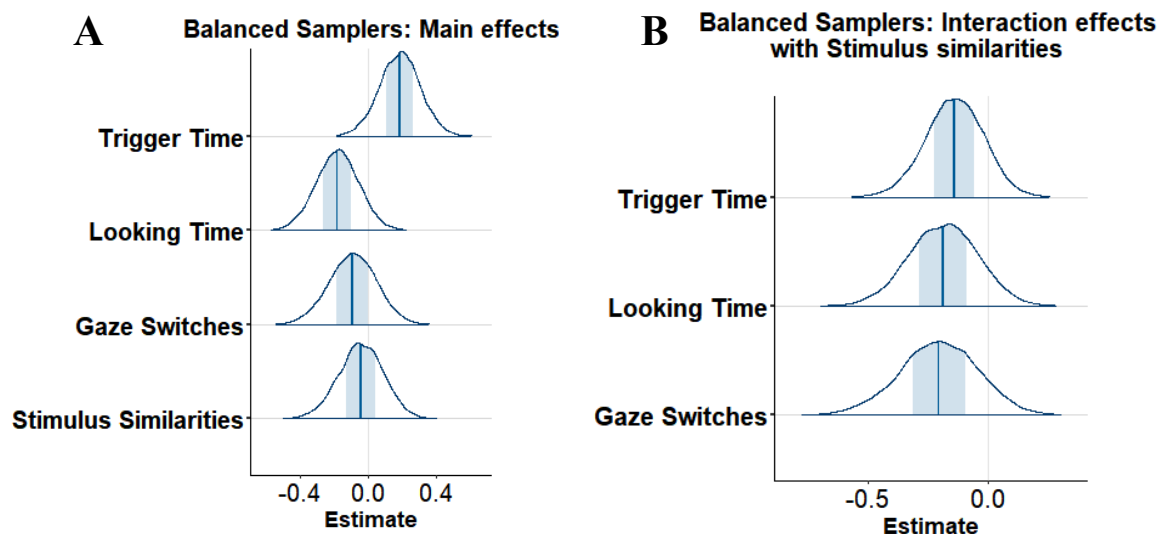
1103 samplers, we decided to look at this group in isolation. This model included 405 observations

1104 and fit successfully. Indeed, main effects and interaction effects were comparable to the other
 1105 two stimulus-dependent models, and therefore in line with the notion that those were mostly
 1106 driven by this group. Here, looking time ($\hat{b} = -0.18$, 95%-CI[-0.43; 0.06]) and trigger time (\hat{b}
 1107 $= 0.18$, 95%-CI[-0.05; 0.42]) had similarly strong effects, whereas both, gaze-shifts ($\hat{b} = -$
 1108 0.09 , 95%-CI[-0.37; 0.18]) and stimulus similarities ($\hat{b} = -0.04$, 95%-CI[-0.31; 0.21]) were
 1109 only marginally negatively associated with higher likelihood to switch. All three interaction
 1110 effects are again negative, meaning a strengthening of looking-time and gaze-shift effects and
 1111 a weakening of the trigger-time effect for higher stimulus similarities.

1112

1113 **Figure S5**

1114 *Effects for Balanced Samplers in isolation*



1115 *Note.* Main effects (A) and interactions (B) of the predictors on the likelihood to switch when
 1116 isolating the cluster of balanced samplers. **A:** Probability distributions for each main effect of
 1117 the predictors on the outcome variable, including stimulus similarities. **B:** Probability
 1118 distributions for each interaction effect between the stimulus similarities and each predictor.

1119 **S2 Adult Experiment**

1120 **S2.1 Similarity Ratings**

1121

1122 The novel stimuli used in the reported infant study were taken from the open TarrLab¹
1123 repository. Two species of *Fribbles* from different families were chosen, under the
1124 consideration of not having a dominantly salient, variable body part (Barry et al., 2014).
1125 Perceptual differences between two stimuli from the same species, then, are mainly defined by
1126 counting the body parts in which they differ (0 to 4) as the variations are nominally different
1127 (Williams, 1998). However, it may be that subjective similarity between the stimuli does not
1128 perfectly map onto this objective way of categorising the differences (see Barry et al., 2014
1129 with different stimulus sets) but could allow for more nuanced, perceptual measures of
1130 similarity. Thus, the aim of this supplementary study was to collect similarity ratings for each
1131 possible pair of the 30 stimuli for each category to account for subjective rather than objective
1132 measures. We collected the ratings for each possible pair as the presentation of stimuli in the
1133 study was randomised without repetition. This led to 465 possible pairs per category. To
1134 minimise fatigue effects, each participant was asked to only rate 155 pairs from one category.
1135

1136 **S2.2 Methods**

1137 **S2.2.1 Participants**

1138 Participants were recruited over Prolific (www.prolific.co) [2021] and the final sample
1139 consisted of 45 participants who completed the study (Mean age = 27.41, range = 18 to 54
1140 years, 52.4% female) so that each individual pair would be rated seven times. One additional
1141 participant was excluded as they left the experiment after 12 trials. Prolific suggests to shortly
1142 inspect the data visually before accepting or rejecting submissions as one shortcoming of these
1143 online platforms is that participants sometimes do not submit high quality data. Based on such
1144 inspection, three further participants were messaged about their very short rating times
1145 suggesting a lack of attention necessary for conscious assessments. They admitted to these
1146 worries based on fatigue from earlier experiments and returned their submissions voluntarily.
1147

1148 S2.2.2 Materials

1149 **S2.2.2.1 Stimuli.** Novel stimuli were taken from the open TarrLab¹ repository. Species
1150 FA2 and FB4 were chosen from which 30 stimuli were semi-randomly selected each, in
1151 alternating triplets to sample from the full range of body-part variations including objective
1152 differences of all four distances (0-4, Williams, 1998; the full list of included stimuli can be
1153 found in the appendix and supplementary online materials).

1154 **S2.2.2.2 Design & Measures.** The study was created with PsychoPy3 and online
1155 conducted via Pavlovia. First, a list of all possible combinations of stimuli per category was
1156 created. Each list was randomly ordered and separated into three equal sets of 155 pairs. This
1157 was based on the consideration to not ask for too many ratings per participant to ensure high
1158 quality data. Each pair then was presented in random order, where the two stimuli were
1159 presented next to each other on grey background for 2 seconds to allow only for a subjective
1160 impression of the similarities rather than counting the differences (Barry et al., 2014). Each
1161 pair was then rated on a scale from 1 (not similar at all) to 7 (extremely similar). After every
1162 52 stimuli (roughly each third), the participant could take a little break which they could
1163 terminate by pressing 'space' but which also automatically ended after 20 seconds.

1164 **S2.2.2.3 Exclusion criteria.** Besides the ratings for each pair, the reaction times for
1165 each rating was recorded. This was used as a rough indication of data quality as reaction times
1166 below 200ms are typically viewed as too short to be conscious and even more so if two stimuli
1167 had to be compared. Thus, if the reaction times were too often in the area of 0.1-0.4 seconds
1168 when roughly inspecting the data visually, we suspected a lack of attention and contacted the
1169 anonymous participant for a follow up. This kind of inspection was only conducted if the
1170 completion time was suspiciously low or high – in accordance with Prolific's data quality check
1171 suggestion. Out of 45 participants, only three were inspected and contacted this way leading to
1172 them returning their submissions voluntarily after admitting they had not completed the study
1173 giving their full attention. While this was a subjective exclusion criterion, it did allow for
1174 economical recruitment where submissions of clearly lacking data quality were not paid for,
1175 but the participants were also not reprimanded by having their submission rejected.

1176

1177 S2.2.3 Analysis

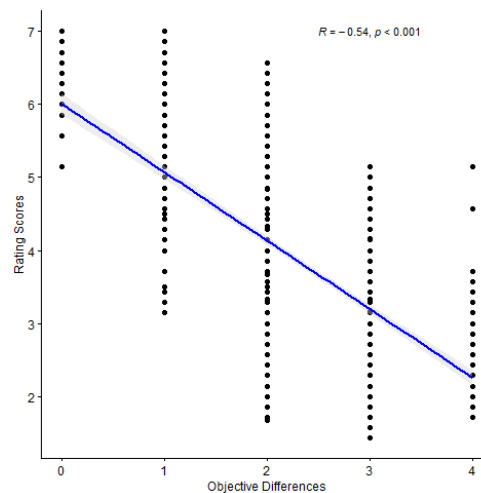
1178 21 ratings with a reaction time of below 200ms were excluded as these could not be
1179 assumed to have been made consciously. Each of these ratings belonged to a different stimulus
1180 pair leading to 21 out of 930 pairs receiving six instead of seven scores included in their

1181 aggregates. We computed the objective difference count for each pair, as well as the mean
1182 score, standard deviation, and range. To investigate the relation between objective and
1183 subjective scores, a correlation analysis was conducted and plotted.

1184 **S2.3 Results**

1185 The Shapiro-Wilk normality tests indicated that the data for both variables – objective
1186 differences and mean rating scores – were not normally distributed ($p < 0.001$). Thus, a
1187 parametric Kendall rank correlation test was computed. This analysis estimated the rank-based
1188 measure of association between the two variables to be significantly correlated, so that the
1189 mean similarity scores decreased with the number of differing body parts ($r_{\text{tau}} = -0.54, p <$
1190 0.001). In other words, stimuli were perceived as more similar the more body parts they had in
1191 common. As the relation, however, was not exactly one to one, we chose to include these
1192 subjective mean scores in any further analyses instead of the objective nominal values as they
1193 were deemed more indicative of the perceived differences between consecutively presented
1194 stimuli.

1195



1196

1197 **2.4 Discussion**

1198 We conducted this supplementary study of collecting similarity ratings between every
1199 possible pairing amongst the stimuli included in the related exploration studies. We found that
1200 the number of objective differences significantly correlated with the subjective similarity
1201 ratings so that mean scores decreased with increasing objective differences. This confirms that
1202 objective differences were also subjectively perceived. However, as the relation was not perfect
1203 – for instance, pairs of identical stimuli received a number of scores different from the
1204 maximum score (7) – this also shows that including the subjective scores may better represent

1205 the subjective perception of consecutively presented stimuli more so than referring to the
1206 objective measure. The findings of this study are in accordance with Barry et al. (2014) who
1207 also found a strong relation between the two whilst suggesting that the objective scores cannot
1208 perfectly indicate subjective perception.
1209