

36 **Abstract**

37 Visual processing in parietal areas of the dorsal stream facilitates sensorimotor
38 transformations for rapid movement. This action-related visual processing is hypothesized to
39 play a distinct functional role from the perception-related processing in the ventral stream.
40 However, it is unclear how the two streams interact when perceptual identification is a
41 prerequisite to executing an accurate movement. In the current study, we investigated how
42 perceptual decision-making involving the ventral stream influences arm and eye movement
43 strategies. Participants ($N = 26$) moved a robotic manipulandum using right whole-arm
44 movements to rapidly reach a stationary object or intercept a moving object on an augmented-
45 reality display. On some blocks of trials, participants needed to identify the shape of the object
46 (circle or ellipse) as a cue to either hit the object (circle) or move to a pre-defined location away
47 from the object (ellipse). We found that during perceptual decision-making, there was an
48 increased urgency to act during interception movements relative to reaching, which was
49 associated with more decision errors. Faster hand reaction times were correlated with a
50 strategy to adjust the movement post-initiation, and this strategy was more prominent during
51 interception. Saccadic reaction times were faster and initial gaze lags and gains greater during
52 decisions, suggesting that eye movements adapt to perceptual demands for guiding limb
53 movements. Together, our findings suggest that the integration of ventral stream information
54 with visuomotor planning depends on imposed (or perceived) task demands.

55

56 **New and Noteworthy**

57 Visual processing for perception and for action are thought to be mediated by two specialized
58 neural pathways. Using a visuomotor decision-making task, we show that participants
59 differentially utilized online perceptual decision-making in reaching and interception, and that
60 eye movements necessary for perception influenced motor decision strategies. These results
61 provide evidence that task complexity modulates how pathways processing perception versus
62 action information interact during the visual control of movement.

63

64 Introduction

65 Many functional sensorimotor skills require rapid visual processing and perceptual
66 decision-making. A very commonly encountered situation during driving is when drivers must
67 decide whether to yield or stop at an intersection. The decision should be made from a
68 distance by judging the shape of the sign at an intersection. If the shape is judged as a stop
69 sign, the driver would slowly press their foot on the brake to bring the car to a gradual stop.
70 However, if the shape is judged as a yield sign, the driver might just slow down or even hit the
71 accelerator if there is no incoming traffic. The driver's ability to make the correct decision and
72 movement depends on efficient real-time processing of visual sensory information in the two
73 visual processing streams (Goodale and Milner 1992; Mishkin et al. 1983). The distance
74 between the sign and the car, the presence of other incoming traffic, and the associated motor
75 actions are likely processed by the posterior parietal cortex along the dorsal visual stream
76 (Culham et al. 2006; Rizzolatti et al. 2002; Rizzolatti and Matelli 2003). The shape and
77 symbols on the sign are perceived by the lateral occipital and inferior temporal cortex along the
78 ventral visual stream (Ales et al. 2013; Grill-Spector et al. 2001; Lehky and Tanaka 2016;
79 Schwartz et al. 1983). Though the contributions of these streams to visuomotor and
80 visuo-perceptual processing is well delineated, it is still unclear how these two streams interact
81 and process sensory information in real-time to facilitate rapid visuomotor actions.

82 The goal of the present study was to understand how engaging the ventral stream
83 affects the spatiotemporal course of movement selection and execution. Many behavioral
84 (reviewed in Gallivan et al. 2018; Hecht et al. 2008; Rosenbaum et al. 2007; Song and
85 Nakayama 2009) as well as neurophysiological studies (reviewed in Cisek and Kalaska 2010)
86 have provided empirical support for simultaneous specification of competing motor plans in the
87 dorsal visual stream. Rapid movement modifications have also been shown when a perceptual
88 decision is made based on ventral stream related attributes, such as object color or shape
89 (Cressman et al. 2007; Schmidt 2002; Song and Nakayama 2008; Veerman et al. 2008),
90 though at slower time scales than motor decisions based on dorsal stream processing of
91 spatial or motion-related properties (Day and Lyon 2000; Franklin et al. 2016; Gritsenko et al.
92 2009; Sarlegna and Mutha 2015). These results imply that despite functionally segregated
93 roles, goal-directed visuomotor actions ultimately necessitate online interaction between the
94 ventral and dorsal streams (Gallivan and Goodale 2018; Milner 2017; Song and Nakayama
95 2009).

96 In these previous studies, the movement required is typically a simple reach executed to
97 a spatially defined goal. However, the capacity for integration of ventral stream information with
98 online decision-making and motor planning may depend on the computational complexity of
99 the movement (van Polanen and Davare 2015). In contrast to simple reaching, interception
100 movements present a challenge for the motor system due to the uncertainty in estimating the
101 velocity and future position of the target and in specifying an appropriate motor plan to hit the
102 target at the desired time and location (Brenner and Smeets 2009; Merchant et al. 2009; Zago
103 et al. 2009). Humans can achieve high interception accuracy via continuous updating of
104 movement trajectories under visual feedback control (Brenner and Smeets 2018), but it is
105 unclear how these interception mechanisms may be modulated by perceptual decision
106 processes mediated by the ventral visual stream.

107 In the present study, we developed a rapid visuomotor decision-making task where
108 participants were asked to make reaching or interception movements under relatively fast or
109 slow time constraints. In some blocks of trials, participants were simply required to hit a

110 stationary (reaching) or moving (interception) object as quickly and as accurately as possible.
111 In separate blocks, participants needed to select among two alternative actions that required
112 correctly identifying the object's shape (hit the circle and avoid the ellipse). Our first hypothesis
113 was that engaging the ventral stream would elicit stronger interference between ventral and
114 dorsal stream processes during interception than reaching movements. We predicted that both
115 decisional and aiming accuracy would be lower for interception movements.

116 In contrast to fixations on static targets during reaching movements, smooth-pursuit eye
117 movements track moving targets and engage additional neural resources (Lencer and
118 Trillenber 2008; Lisberger 2015) during interception movements. Once the moving target is
119 stabilized on the retina, the limb motor system may rely on oculomotor efferent signals during
120 pursuit eye movements to perform continuous retinotopic to limb-centric coordinate
121 transformations (Gauthier et al. 1990) and guide limb movements. The neural regions involved
122 in eye movement processing overlap with those involved in decision-related signals (Fooker
123 and Spering 2019; Gold and Shadlen 2007; Heekeren et al. 2008; Joo et al. 2016), and this
124 likely affects recognition of object features during fast smooth-pursuits (Ludvigh and Miller
125 1958a; Schutz et al. 2009; Westheimer and McKee 1975). Thus, our second hypothesis was
126 that when the ventral stream is engaged during interception movements, the oculomotor
127 signature of pursuit eye movements will change. Specifically, we expected higher gaze gains
128 (computed as ratio of gaze velocity and target velocity) during perceptual decisions.

129

130 **Methods**

131 *Participants*

132 Twenty-six healthy, right-handed participants (16 women; 23.7 ± 5.5 years) completed
133 the experiment. All participants had no known history of neurological disorders and had normal
134 or corrected-to-normal vision. Each participant provided written informed consent prior to
135 participating and were compensated for their participation. All study procedures were approved
136 by the Institutional Review Board at the University of Georgia.

137

138 *Apparatus*

139 Participants were seated in a chair and used their right hand to grasp the handle of a
140 robotic manipulandum that could move in a horizontal plane (KINARM End-Point Lab, BKIN
141 Technologies, Kingston, Ontario, Canada) (see Fig.1A). All visual stimuli were projected at 60
142 Hz onto a semi-transparent mirror from a monitor above the workspace. This set-up allowed
143 the stimuli to appear on the same horizontal plane as the handle and to occlude direct vision of
144 the hand. During task performance, the robot applied a small background load (-3 N in the Y
145 direction) to the handle and recorded movement position and velocity at 1000 Hz. The
146 monocular eye position of each participant was recorded at 500 Hz using a video-based
147 remote eye-tracking system (Eyelink 1000; SR Research, Ottawa, ON Canada) integrated with
148 the robot and calibrated for the 2D horizontal workspace. Data from the eye-tracker and robot
149 were time-synced offline using MATLAB (version 9.5.0; The MathWorks, Natick, MA).

150

151 *Experimental design and procedure*

152 Participants performed rapid whole-arm reaching and interception movements in which
153 they were instructed to either hit or avoid an object based on the object's shape. At the
154 beginning of each trial, participants moved a cursor (white circle, 1 cm diameter) representing
155 their veridical hand position to a start position (yellow circle, 2 cm diameter) located at the

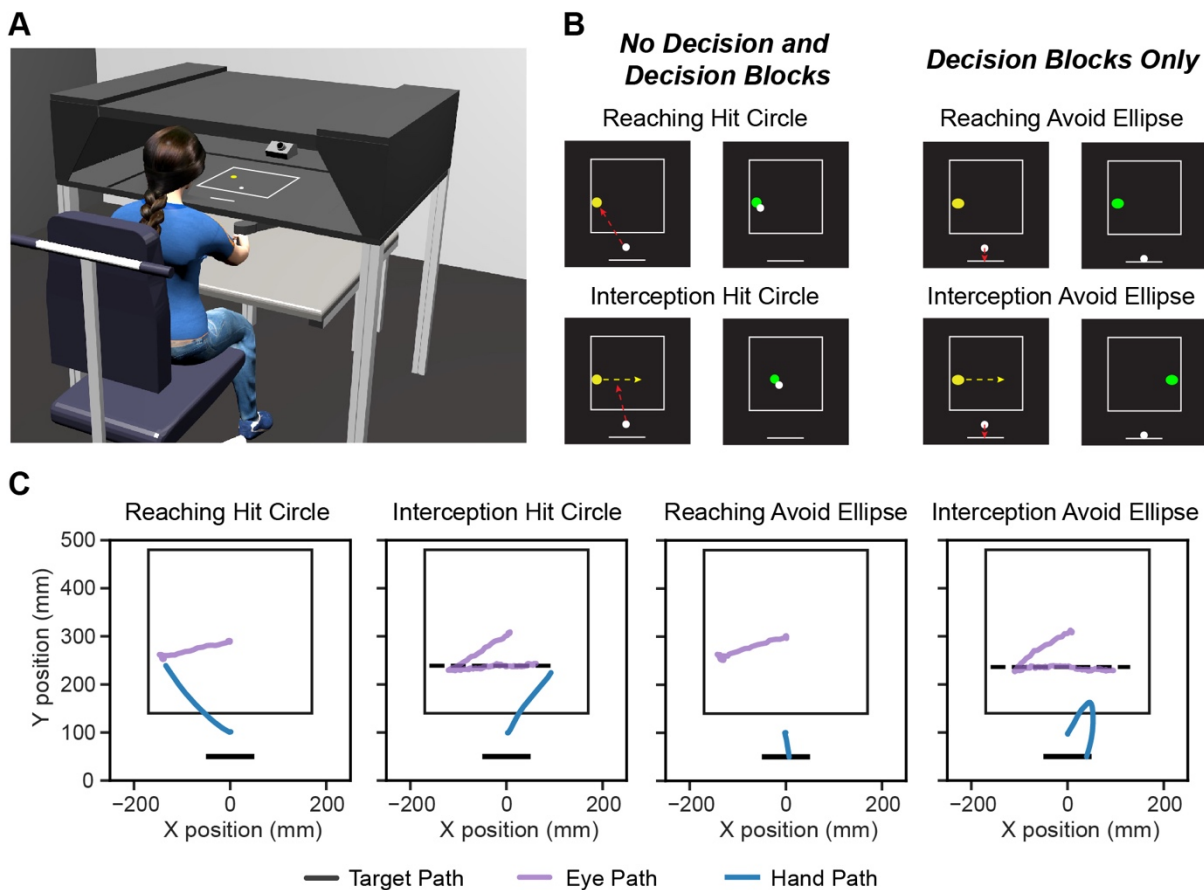
156 midline of the visual display ($x=0$). After reaching the start position, a fixation cross appeared at
157 the midline 22 cm from the start position in the Y direction. Participants were required to
158 maintain fixation and keep their hand at the start position for 500 ms, after which the fixation
159 cross and start position disappeared.

160 Following a fixed 200 ms delay, a yellow object was presented on the display near
161 either the left or right edge of a rectangular box (34 x 34 cm) centered on the midline and 22
162 cm above the start position (see Fig. 1B). The possible object shape on a given trial, and the
163 participant's task, depended on the experimental block. During No Decision blocks,
164 participants were informed that the object shape would always be a circle (2 cm diameter), and
165 that they should hit the circle as quickly and as accurately as possible. A "hit" was recorded
166 when the cursor first touched the circle—participants were not required to stop at the circle.
167 During Decision blocks, participants were informed that the object would appear as either a
168 circle or an ellipse (major axis = 2.3 cm; minor axis = 2 cm) with equal probability. The lengths
169 of the ellipse axes were selected based on pilot experiments to ensure that the object must be
170 foveated to differentiate it from a circle. As in the No Decision blocks, if the participants saw a
171 circle, they were instructed to hit it as quickly and as accurately as possible. However, if an
172 ellipse appeared, participants were instructed to avoid hitting the ellipse and instead move in
173 the opposite direction toward a horizontal bar (10 cm width) centered on the midline and -4 cm
174 from the start position in the y direction (see Fig. 1B). Thus, in contrast to No Decision blocks,
175 in which participants could simply plan to hit the object on every trial, Decision block trials
176 required the participant to accurately identify the object shape in order to perform the correct
177 action (i.e., hit the circle or avoid the ellipse). Therefore, in addition to the No Decision blocks,
178 the Decision condition required two additional steps, object identification and selection of an
179 appropriate motor plan.

180 For each block of trials, the object either moved horizontally across the display
181 (Interception) or remained in the same position (Reaching). On Interception trials, the object
182 appeared ± 16 cm to the left or right of the midline (Y position range 14.5 - 17 cm from the start
183 position, uniform distribution) and traversed at a constant Euclidean velocity of ± 40 cm/s (Fast)
184 or ± 34 cm/s (Slow) toward the other horizontal boundary of the rectangular box. The varying
185 object velocity was added to test the hypotheses under stricter conditions of time constraints.
186 On Reaching trials, the object appeared to the left or right of the midline with starting positions
187 drawn from a uniform distribution (X position range: ± 13 - 16 cm from midline; Y position range
188 14.5 - 17 cm in front of start position) and remained stationary. For both types of trials, the
189 object remained on the visual display until it was hit or for the maximum trial duration. On
190 Interception trials, the maximum trial duration equaled the time it took for the object to arrive at
191 the horizontal boundary given its velocity: 800 ms for fast velocities (± 40 cm/s) and 950 ms for
192 slow velocities (± 34 cm/s). To match the Interception trial durations, objects remained on the
193 screen for a maximum of 800 ms (Fast) or 950 ms (Slow) during Reaching trials. Before each
194 block, participants were informed about the object motion (moving or stationary) but were not
195 given any information about the object speed or trial duration.

196 Performance feedback was provided for 500 ms once the object was hit (i.e., the cursor
197 overlapped with the object) or the maximum trial duration was reached. If a circle was correctly
198 hit, the circle would turn green; if the circle was missed it would turn red. An ellipse would turn
199 red if it was incorrectly hit instead of avoided and would turn green if correctly avoided. The
200 next trial began following a 1500 - 2000 ms delay.

201 Participants performed 8 experimental blocks of 90 trials each (720 trials total). Block
202 order was counterbalanced across participants. Each experimental block consisted of a unique
203 combination of decision type (No Decision or Decision), movement type (Reach or Intercept),
204 and trial duration (Fast or Slow). Object shape (during Decision blocks) and the object start
205 location were randomized across trials within each block.
206



207
208 *Figure 1: Experimental design and example trials. A: Experimental setup. Participants moved a robotic*
209 *manipulandum with their right hand to control a cursor (white circle) in response to an object (yellow circle) on the*
210 *visual display. A remote gaze-tracker at the back of the workspace recorded eye positions in Cartesian*
211 *coordinates of the workspace. B: Trial types. On every trial, participants were instructed to hit or avoid depending*
212 *on object shape (hit circle, avoid ellipse). No Decision blocks consisted of only circles; Decision blocks mixed*
213 *circle and ellipse trials with equal probability. Participants either reached a stationary object (Reaching) or*
214 *intercepted a moving object (Interception). The object turned green for correct hits (circle hits) and red for*
215 *incorrect (if ellipses were hit). Similarly, if a circle was missed, it turned red at the end of the trial (Fast blocks trial*
216 *duration: 800 ms; Slow blocks: 950 ms), and if movement was made towards the bar when an ellipse appeared in*
217 *the workspace, it turned green at the end of the trial. C: Sample 2D eye and hand paths for each trial type from a*
218 *representative participant.*

219 Data Analysis

220 All hand and eye movement data were analyzed using MATLAB (version 9.5.0, The
221 MathWorks, Natick, MA) and Python (version 3.7). Statistical analyses were performed in R
222 (version 3.6.0).
223

224 *Arm Movements*

225 Hand position and velocity data were first smoothed using a fourth-order Butterworth
226 low-pass filter with a 5 Hz cutoff. Movement onset was defined as the time the tangential
227 velocity first exceeded 5% of the first local peak. Reaction time (RT) was calculated as the time
228 from appearance of object in the workspace to movement onset. Trials were excluded if there
229 was no identifiable RT or if RT was less than 100 ms (1.4% of all trials). Trials were also
230 excluded if participants received correct feedback despite inaccurate motor performance; this
231 was the case when the participant hit the circle only after missing the object on the initial
232 attempt (2.3% of all trials). Peak speed (PS) was defined as the maximum tangential velocity
233 of the hand position at the first local peak. Since PS could differ depending on the object
234 decision in Decision blocks, only trials in which the participant continually moved toward the
235 circle throughout the trial were included (49.3% of all Decision trials).

236 For each trial, we examined the hand kinematics to determine decisional and motor
237 performance accuracy at different stages of the movement. The initial direction (ID) of the
238 movement was calculated as the angle between the midline and the vector linking the hand
239 position at the start to the hand position at peak acceleration. In Decision blocks, the initial
240 decision was based on the ID of the movement: movements were classified either as being
241 aimed toward the object or toward the bar. Initial decision errors were computed for each
242 participant as the percentage of trials in which the initial decision did not match the expected
243 movement direction given the true object identify (i.e., aimed toward the bar on trials with a
244 circle or aimed toward the object on trials with an ellipse). Likewise, final decision errors were
245 calculated as the percentage of trials the participants' final hand position was closer to the bar
246 on circle trials or closer to the object on ellipse trials. Trials in which the initial decision and the
247 final decision were different (e.g., aimed toward the circle but attempted to hit the bar) were
248 classified as "redirect" movements, indicating a change-of-mind after movement initiation
249 (Resulaj et al. 2009). We quantified both the total percentage of redirect movements across all
250 Decision trials, as well as the percentage of initial decision errors that were redirected. This
251 latter index characterizes how well participants were able to correct wrong initial decisions
252 online.

253 Finally, to compare motor performance across No Decision and Decision blocks, we
254 calculated aiming accuracy on trials continually directed toward the circle (i.e., all valid No
255 Decision trials and Decision circle trials in which both the initial and final decision were
256 correct). An *aiming error* was defined as whenever the hand position reached the Y-position of
257 the object, but nevertheless did not successfully hit the object before the trial elapsed.

258 *Eye Movements*

260 Details of gaze processing and gaze-event identification are provided in more detail in
261 previous work (Singh et al. 2017; Singh et al. 2016). Briefly, gaze data were low-pass filtered
262 at 20 Hz and preprocessed to remove blinks, one-sample spikes (due to incorrect detection of
263 corneal reflection), and screen outliers (due to instances when gaze drifts outside the
264 workspace). Gaze events were identified as saccades and fixations using adaptive velocity
265 and acceleration thresholds (Singh et al. 2016). Our previous analyses showed that velocity
266 thresholds vary substantially between participants but that acceleration threshold is relatively
267 constant ($6,000^\circ/\text{s}^2$). For each velocity peak that exceeded the velocity threshold, we
268 confirmed that the peak acceleration leading up to the velocity peak also exceeded the
269 acceleration threshold. If both thresholds were exceeded, we classified the gaze event as a

270 saccade. For each saccade, we found the first inflection point before and after the local peak in
271 gaze angular velocity. Saccade onset corresponded to the first inflection point before the local
272 peak in gaze angular velocity. Saccade offset was determined by starting at the first inflection
273 point after the local peak in gaze angular velocity and finding the first point in time at which the
274 gaze velocity and acceleration remained continuously lower than the respective thresholds for
275 at least 40 ms.

276 For interception movements, smooth-pursuits were identified when gaze and target
277 locations and velocities were continuously within a *foveal visual radius* as described in Singh et
278 al. (2016). Briefly, because targets were presented in a transverse plane, the foveal visual
279 radius accounts for larger spatial distances for the same foveal visual acuity (2-3°) when the
280 objects were presented farther away from the body. Note that a gaze event was only classified
281 as a smooth-pursuit if the target was foveated. Individual saccades were discarded if the
282 duration was <5 ms, and smooth-pursuits/fixations were discarded if the duration was <40 ms.
283 On some trials, participants made predictive saccades anticipating the location of the object.
284 Since we were only concerned with visually-guided performance, we eliminated any saccade
285 initiated <100 ms after target onset and any initial saccade not directed to the object (>100 mm
286 from object). Following exclusion of individual saccades, we defined a valid trial for the task as
287 one containing an initial saccade to the target followed by a fixation or smooth-pursuit. Thus,
288 gaze for a trial was not analyzed if the trial did not contain a valid saccade and a gaze event
289 (fixation or pursuit) or if a gaze event (fixation or pursuit) occurred before any saccade. Overall,
290 gaze data were included for 90.7% of Reaching trials and 88.6% of Interception trials. Data
291 from two subjects were not included in the eye movement analyses because fewer than 50%
292 of their trials were identified as valid according to the above criteria.

293 Saccadic reaction time (SRT) for both Reaching and Interception trials was calculated
294 as the onset of the initial saccade for a given trial. For interception movements, we also
295 determined the gaze lag as the horizontal distance (mm) between the moving object and the
296 eye position at the end of the first saccade, and throughout the gaze duration (excluding catch-
297 up saccades occurring during the smooth-pursuit period). Gaze gain was calculated as the
298 gaze angular velocity divided by the object angular velocity and average gain was quantified
299 for the open-loop (15-100 ms of gaze), first 100 ms of the closed-loop (next 100 ms of gaze),
300 and full closed-loop (gaze after first 100 ms) phases (excluding catch-up saccades). Gaze gain
301 for the first 15 ms was not analyzed due to the potential for artificially high velocities from the
302 offset of the preceding saccade. Removal of the first 15 ms did not affect differences in gaze
303 gain across conditions. Of note, smooth-pursuit gains are typically computed using eye-
304 trackers with chin rests (Brostek et al. 2017; Churchland and Lisberger 2002) or eye-trackers
305 that are head-mounted (Spering et al. 2005). With these eye-trackers, gaze movements are
306 computed as eye-in-head movements. In contrast, we used a remote eye-tracker which
307 allowed small head movements to occur. Thus, we chose to report gaze gains instead of
308 smooth-pursuit gains (Barnes 1993; Ranalli and Sharpe 1988). Finally, we determined the
309 number of catch-up saccades as a function of time after gaze onset and quantified the average
310 number of catch-up saccades during the entire gaze duration.

311 312 *Statistical Analyses*

313 To assess how the introduction of perceptual decision-making influenced RT, PS, and
314 SRT, we computed the means for each combination of decision type, movement type, object
315 velocity, and object start location (left or right). We then subtracted the No Decision block

316 means from the Decision block means, separately for each participant and movement type/
317 trial duration combination. A one-sample *t*-test was used to determine whether the change
318 between Decision and No Decision means were significantly different from zero, and a 2
319 (Reaching or Interception) x 2 (Fast or Slow) repeated-measures ANOVA assessed whether
320 the effect of decision-making differed across movement type and trial duration. Measures of
321 decision-making and hand and eye motor performance were assessed across conditions using
322 repeated-measures ANOVAs. For all ANOVA tests, the alpha level was set at 0.05 and effect
323 sizes are reported using generalized η^2 . Post hoc pairwise comparisons were conducted using
324 the Holm correction (Holm 1979). Linear regression was used for bivariate comparisons, with
325 alpha set to 0.05, and the statistical comparison of correlations between conditions was
326 evaluated using the Dunn and Clark's *z* for dependent groups with nonoverlapping variables
327 (Dunn and Clark 1969), as implemented in *cocor* package in R (Diedenhofen and Musch
328 2015).

329

330 Results

331

332 *Final decision errors occurred more frequently for interception than reaching movements*

333 In the task, participants made rapid eye and arm movements in response to an object
334 appearing on the visual display. As illustrated in Figure 1C, after object onset participants
335 typically made saccades directly to the object, followed by fixation on a stationary object near
336 the right or left edge of the display boundary (Reaching trials) or pursuit of an object moving at
337 a constant Euclidean velocity from one boundary to the other (Interception trials). Participants
338 either attempted to hit any circle that appeared by moving the cursor (representing hand
339 position) to the object before the end of the trial or avoid any ellipse that appeared by moving
340 in the opposite direction toward a bar on the display.

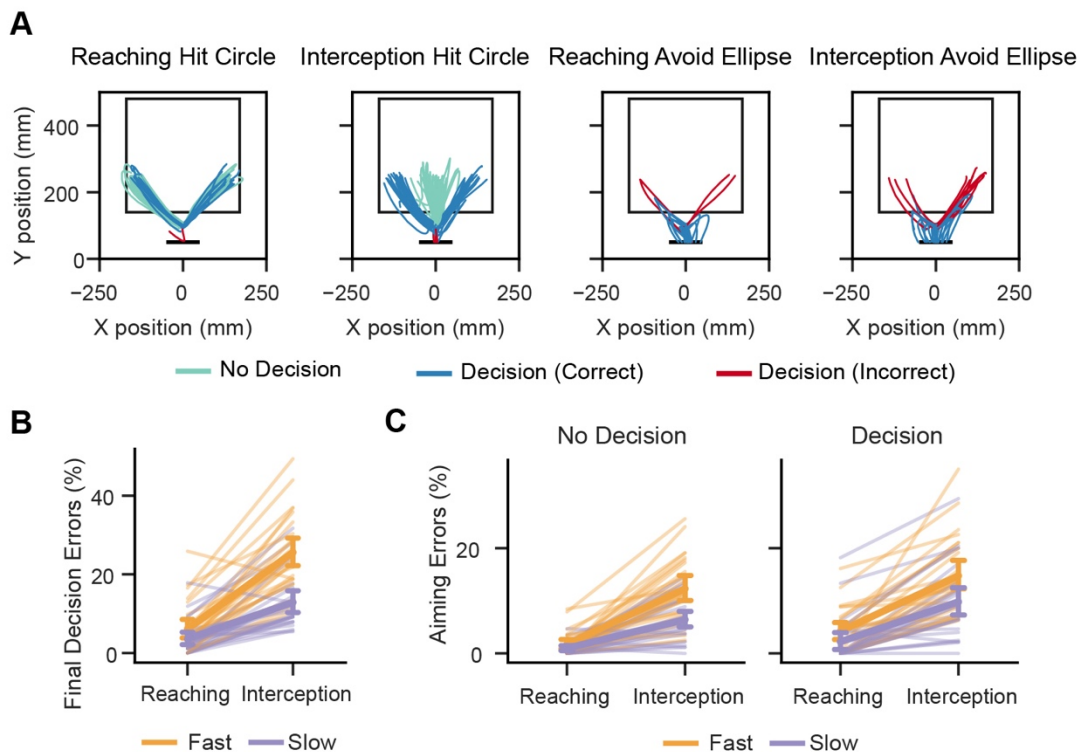
341 Figure 2A shows the hand trajectories for a representative participant. Each line
342 indicates the hand path from object onset until the participant hit their intended target (object or
343 bar), or until the maximum trial duration (if neither the object nor the bar was hit). During No
344 Decision blocks, the object was always a circle, whereas in Decision blocks, the object could
345 be either a circle or ellipse. The addition of the decision-making task component led to clear
346 differences in where participants chose to intercept the object. In No Decision blocks, on
347 average, participants tended to intercept the object slightly after it crossed the midline ($M =$
348 20.1 ± 5.9 mm from midline). In contrast, there was a significant shift in object hit locations
349 during Decision blocks ($M = 75.0 \pm 5.6$ mm from midline) [main effect of decision: $F(1,25) =$
350 228.77 , $p < 0.001$, $\eta^2 = 0.66$]. As expected, interceptions were made later when the object was
351 moving faster [main effect of trial duration: $F(1,25) = 110.32$, $p < 0.001$, $\eta^2 = 0.13$].

352 In Decision blocks, final decisions were classified as either correctly attempting to hit the
353 circle or avoid the ellipse, or incorrectly attempting to hit the ellipse or avoid the circle (Fig. 2B).
354 The percentage of final decision errors was higher for interceptions than for reaching
355 movements [main effect of movement type: $F(1,25) = 113.03$, $p < 0.001$, $\eta^2 = 0.52$] and for
356 faster trial durations [main effect of trial duration: $F(1,25) = 107.72$, $p < 0.001$, $\eta^2 = 0.23$]. The
357 increase in errors at faster durations was larger for interceptions [interaction of movement type
358 and trial duration: $F(1,25) = 47.38$, $p < 0.001$, $\eta^2 = 0.12$], indicating that faster object velocity
359 reduced interception decision accuracy beyond decreasing the time possible to hit the object.

360 For Decision blocks, we then computed aiming errors for only those trials where the
361 final decision was correct. As expected, the additional computational costs associated with

362 estimating object velocity and movement timing led to more aiming errors during interception
 363 movements. In both No Decision and Decision blocks, there were a higher percentage of
 364 aiming errors for Interception [main effect of movement type: $F(1,25) = 129.22, p < 0.001, \eta^2 =$
 365 0.43], especially at faster trial durations [interaction of movement type and trial duration:
 366 $F(1,25) = 20.88, p < 0.001, \eta^2 = 0.04$], reflective of the greater difficulty in intercepting an object
 367 at higher speeds (Fig. 2C). There was an increase in aiming errors in Decision blocks [main
 368 effect of decision: $F(1,25) = 11.49, p = 0.002, \eta^2 = 0.06$], but the increase did not differ
 369 between Reaching and Interception [interaction of movement type and decision: $F(1,25) =$
 370 $1.48, p = 0.24, \eta^2 = 0.003$]. Together, these results suggest that during time-constrained
 371 perceptual decision-making, the added task demands of interceptive movements affected the
 372 decisional accuracy more than the motor accuracy.

373



374

375 Figure 2: Final decision errors for interception and reaching movements. A: Sample hand paths from a
 376 representative participant. During No Decision blocks, participants were required to reach or intercept a circle
 377 appearing on the display (green paths, left two panels). During Decision blocks, participants were required to hit a
 378 circle if it appeared (blue and red paths, left two panels), or avoid an ellipse (right two panels). Final decisions on
 379 these trials were classified as correct if the final hand position was closer to the correct location (object or bar)
 380 given the object's identify (blue paths), and incorrect if not (red paths). B: Final decision errors were higher for
 381 interception than reaching and for fast (800 ms) than slow (950 ms) trial durations. C: Aiming errors were higher
 382 for during interception, and aiming errors increased similarly for both reaching and interception during Decision
 383 blocks. Errors were calculated as the percentage of all trials in which the y-position of the object was reached but
 384 the object was not hit. Individual lines represent the means for one participant. Error bars show the 95%
 385 confidence interval of the group mean estimate.

386 *Perceptual decisions increase urgency to act more for interception relative to reaching*

387 One potential strategy participants could have employed in the Decision trials is to
 388 complete the recognition of the object shape before initiating a movement. Such a strategy
 389 would minimize an erroneous commitment to a movement that would later have to be

390 reversed. If this were the case, initial decisions should have been similar between Reaching
391 and Interception movements. In contrast, there was a large increase in initial decision errors
392 during Interception relative to Reaching [main effect of movement type: $F(1,25) = 121.09$, $p <$
393 0.001 , $\eta^2 = 0.48$] (Fig. 3A). Most of these errors (91.4 %) were due to initially aiming toward the
394 ellipse (which had to be avoided), suggesting a default initial strategy of trying to hit rather than
395 avoid the object and then correct the movement if the object shape was correctly identified
396 during the movement. This default strategy was used more often during faster trials [main
397 effect of trial duration: $F(1,25) = 19.09$, $p < 0.001$, $\eta^2 = 0.05$], when there were greater
398 constraints to hit the object in time.

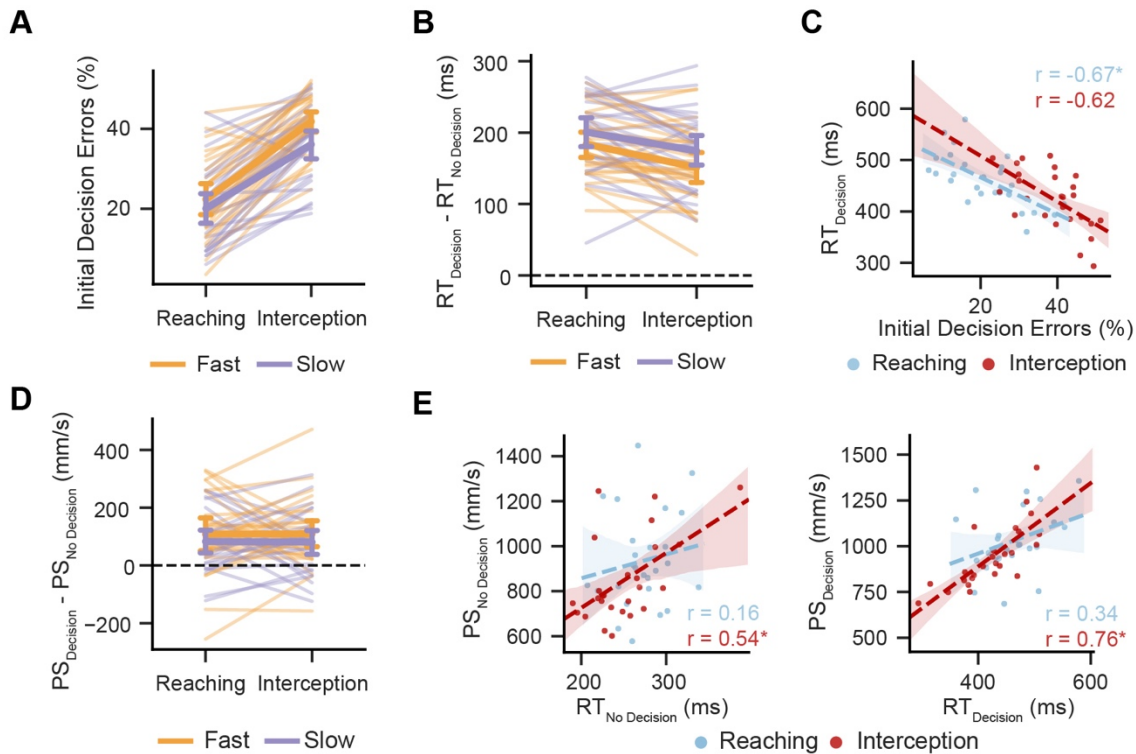
399 As expected, perceptual decision-making led to a significant reaction time (RT) delay.
400 Relative to No Decision blocks, RTs for Decision blocks were on average 178 ± 11 ms longer
401 [$t(1,25) = 20.04$, $p < 0.001$] (Fig. 3B). Thus, perceptual decisions based on ventral stream
402 processing clearly increased the time taken for object identification (circle or ellipse) and motor
403 response selection (hit or avoid). However, the increase in RT for the Decision blocks differed
404 depending on the type of movement and time constraints: RT increase was smaller for
405 Interception [main effect of movement type: $F(1,25) = 13.63$, $p = 0.001$, $\eta^2 = 0.07$], and for Fast
406 movement blocks [main effect of trial duration: $F(1,25) = 9.83$, $p = 0.004$, $\eta^2 = 0.04$]. This
407 suggests that even though decisions added processing time, participants chose to limit pre-
408 movement processing time when an interception was required or under more restrictive time
409 constraints. The increased urgency to act came at the expense of initial decision accuracy:
410 participants with shorter RTs during Decision blocks exhibited more initial decision errors for
411 both reaching and interception movements (Reaching: $r = -0.67$, $p < 0.001$; Interception: $r = -$
412 0.62 , $p < 0.001$) (Fig. 3C).

413 During decision-making, there was also an increase in the speed of the response: on
414 average, peak speed (PS) of movements attempting to hit the object increased by 95.4 mm/s
415 [$t(1,25) = 5.46$, $p < 0.001$] (Fig. 3D). The change in PS did not vary based on movement type
416 [main effect of movement type: $F(1,25) = 0.00$, $p = 0.98$, $\eta^2 < 0.01$] or trial duration [main effect
417 of trial duration: $F(1,25) = 2.70$, $p = 0.11$, $\eta^2 = 0.01$]. For reaching movements, the increase in
418 PS may reflect a general urgency to complete the movement more quickly after a prolonged
419 decision period. For interception movements, where participants have a salient visual cue for
420 time remaining (the object approaching the boundary), changes in PS are likely more directly
421 related to changes in RT: the longer the participant waited to initiate movement, the less time
422 available and longer movement amplitude necessary to hit the object. Indeed, for both No
423 Decision and Decision blocks, there was a significant positive correlation between PS and RT
424 (No Decision: $r = 0.54$, $p = 0.003$; Decision: $r = 0.76$, $p < 0.001$), which was not the case for
425 reaching movements (No Decision: $r = 0.16$, $p = 0.43$; Decision: $r = 0.34$, $p = 0.08$) (Fig. 3E).
426 The PS-RT correlation was significantly greater for Decision, Interception blocks than for No
427 Decision, Reaching blocks ($z = 2.98$, $p = 0.003$), indicating that the lower RTs during decision-
428 making for interception may be in part to allow for slower, shorter movement trajectories.
429 Overall, the results suggest that perceived time constraints—amplified during both interception
430 movements and faster trial durations—encourage earlier movement initiation even if the
431 decision process is incomplete.

432 433 *Interception strategies favor ongoing decision-making after movement initiation*

434 To further investigate how movements are planned relative to time-sensitive decision
435 processing, we analyzed how often participants adjusted their movements online. To do this,

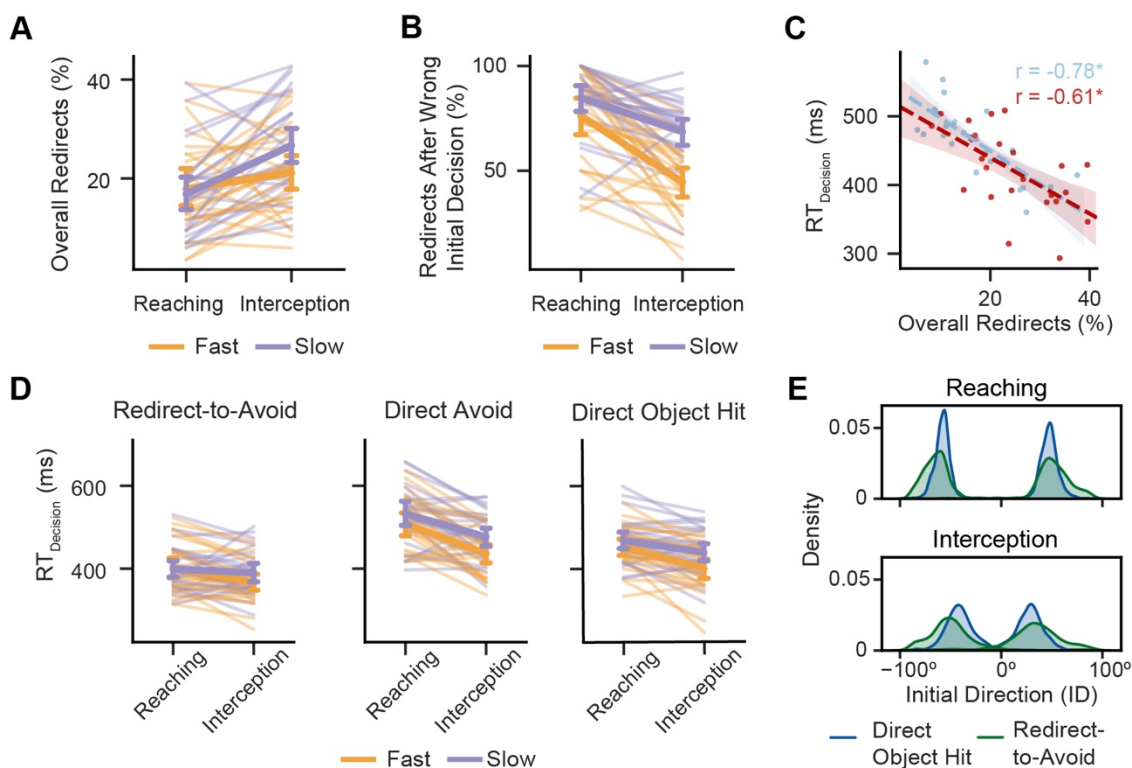
436 we distinguished between “direct” and “redirect” movements. Direct movements were when
 437 both the initial and final decisions were directed toward the object (direct object hit) or to the
 438 bar (direct avoid). Redirect movements occurred when the final decision differed from the initial
 439 decision: as can be seen in Figure 2A, redirects were predominantly observed when the
 440 participant made an initial decision toward the object, only to curve back around to hit the bar
 441 (redirect-to-avoid). The opposite pattern—moving to the object after initially moving to avoid it
 442 (redirect-to-hit), rarely occurred (<0.01% of Decision trials), highlighting the greater accuracy
 443 demands imposed by hitting the object vs. hitting the bar.



444
 445 Figure 3: Reaction times and limb kinematics for interception and reaching movements. A: Initial decision errors
 446 were higher for interception and for fast (800 ms) trial durations. B: The increase in reaction time from No
 447 Decision to Decision blocks was smaller for interception relative to reaching. C: Participants were shorter reaction
 448 times during Decision blocks were exhibited a higher number of initial decision errors. D: Peak speed increased
 449 for Decision blocks similarly for reaching and interception. E: Reaction time and peak speed tended to be more
 450 correlated during interception and Decision blocks. For line plots, individual lines represent the means for one
 451 participant and error bars show the 95% confidence interval of the group mean estimate. For regression plots,
 452 each dot represents the mean value for one participant and shaded area represents the 95% confidence interval
 453 of the regression estimate. * indicates $p < 0.05$.

454 All participants had both direct and redirect movements, indicating a mixture of
 455 strategies used during the task. Overall, redirect movements were more common during
 456 Interception [main effect of movement type: $F(1,25) = 16.82$, $p < 0.001$, $\eta^2 = 0.11$], especially at
 457 Slow trial durations [interaction of movement type and trial duration: $F(1,25) = 9.61$, $p = 0.005$,
 458 $\eta^2 = 0.03$] (Fig. 4A). This suggests that decisions about object shape could be modified after
 459 movement initiation. Furthermore, participants were more likely to rely on this strategy for
 460 complex interceptive movements and when there was more time for online corrections (Slow
 461 trials).

462 Though redirect movements were used more during Interception, they were employed
 463 more effectively during Reaching. As shown in Figure 4B, after an initial decision error, a
 464 correct redirect of an initially wrong decision was more likely to occur for Reaching [main effect
 465 of movement type: $F(1,25) = 50.82, p < 0.001, \eta^2 = 0.30$] and for Slow trial durations [main
 466 effect of trial duration: $F(1,25) = 55.83, p < 0.001, \eta^2 = 0.16$]. Therefore, task difficulty limited
 467 the ability to implement a corrective movement when they were necessary.
 468



469
 470 Figure 4: Redirected movements and Initial Directions (ID) reveal ongoing decision-making after movement
 471 initiation. A: Redirect movements (change between initial and final decision) during Decision blocks were higher
 472 for interception, suggesting more online adjustments after movement initiation. B: Initial decision errors were more
 473 likely to be corrected for reaching and slow trial durations. C: Participants were shorter reaction times during
 474 Decision blocks were exhibited a higher number of redirect movements. Each dot represents the mean value for
 475 one participant and shaded area represents the 95% confidence interval of the regression estimate. * indicates p
 476 < 0.05 . D: Mean reaction times were shortest for redirect-to-avoid movements (initially aimed toward object then
 477 redirected to bar), longest for direct avoid movements (directed toward bar throughout), and intermediate for
 478 direct object hits (directed to object throughout). In all cases, interception reaction times were shorter than those
 479 for reaching. Individual lines represent the means for one participant and error bars show the 95% confidence
 480 interval of the group mean estimate. E: Kernel density estimate of the initial movement direction (0° = aimed at
 481 midline) for redirect-to-avoid and direct object hit movements. IDs were aimed farther from the midline for redirect-
 482 to-avoids during Decision blocks for both reaching (upper panel) and interception (lower panel).

483 If initial decisions were less likely to be corrected, why were participants more likely to
 484 redirect their movements during Interception trials? In Decision blocks, movements might have
 485 been initiated early (during both Reaching and Interception trials) before the perceptual
 486 decision was complete, but once the movements were underway the complexity of the
 487 interception movements may have made it much harder to correct them. If this is the case,
 488 initiation of redirect movements should be associated with shorter RTs. Indeed, for both

489 Reaching and Interception, participants with a higher proportion of redirect movements
490 exhibited shorter decision RTs [Reaching: $r = -0.78$, $p < 0.001$; Interception: $r = -0.61$, $p <$
491 0.001], suggesting a greater reliance on online adjustments and ongoing decision-making after
492 movement initiation (Fig. 4C). Furthermore, there were RT differences depending on the
493 movement strategy (redirect-to-avoid, direct avoid, direct object hit) ultimately executed.
494 Redirect-to-avoid movements (i.e., movements initiated towards ellipse but subsequently
495 corrected) had an average RT of 390 ± 11 ms, relative to 489 ± 15 ms for direct avoids [main
496 effect of movement strategy: $F(1.32, 33.12) = 71.64$, $p < 0.001$, $\eta^2 = 0.35$, Greenhouse-Geisser
497 corrected] (Fig. 4D). The average RT for direct object hits was approximately halfway in-
498 between the RTs for the two types of avoid movements (439 ± 12 ms), reflecting that
499 participants defaulted towards initiating a movement towards the object even when their
500 decision was incomplete. Interestingly, RTs were shorter for Interception than Reaching for
501 redirect-to-avoid, direct avoids, and direct hits [all t 's > 2.2 , all p 's < 0.05], and the RT
502 difference was largest for direct avoids [interaction of movement type and strategy: $F(1.34,$
503 $33.48) = 8.51$, $p = 0.003$, $\eta^2 = 0.02$, Greenhouse-Geisser corrected]. This suggests that simply
504 preparing for an interception movement, even when it was not selected, contributed to earlier
505 movement initiation.

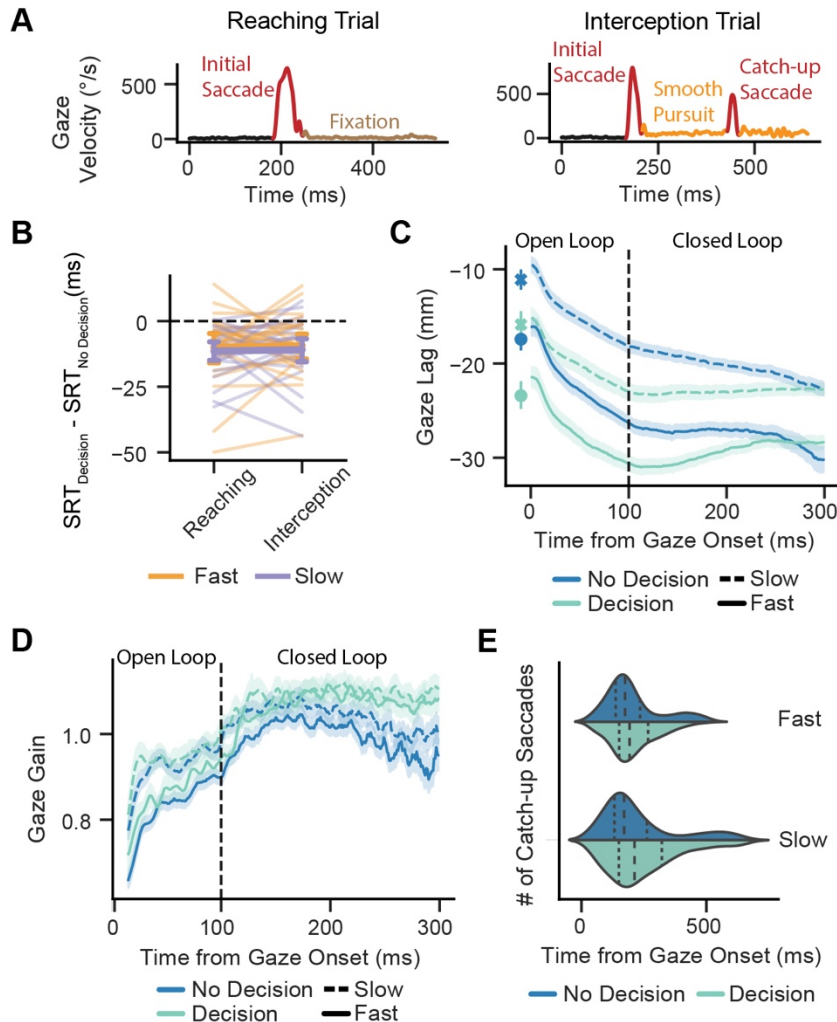
506 A closer analysis of the movement trajectories suggests that the initial movement plans
507 carried a signature of an incomplete decision during movement initiation. Both direct object hit
508 and redirect-to-avoid movements were initially aimed toward the object, indicating an early
509 motor plan to hit the object. However, as shown in Figure 4E, trajectories of movements that
510 were ultimately redirected were on average initially aimed farther from the midline than direct
511 movements (longer tail for redirect-to-avoid) [main effect of movement strategy: $F(1,25) =$
512 131.91 , $p < 0.001$, $\eta^2 = 0.28$], and this difference was larger for Interception [interaction of
513 movement type and strategy: $F(1, 25) = 10.59$, $p = 0.003$, $\eta^2 = 0.01$]. The deviation of the initial
514 direction away from the midline likely reflects an intermediate motor plan between hitting the
515 circle and the bar, suggesting a more conservative approach when the decision is not fully
516 formed.

517
518 *Perceptual decision-making influences eye movement strategies*

519 Saccades and gaze events were identified using a geometric method to transform eye
520 movement data to the horizontal plane and adaptive velocity-based thresholds (Singh et al.
521 2016) for each participant (see Fig. 5A). Standard task performance consisted of an initial
522 saccade followed by onset of gaze (fixation or smooth-pursuit) on the target - we restricted our
523 eye movement analysis to the trials that followed that structure (see Methods for details).

524 As shown in Figure 5B, SRTs during Decision blocks were on average $10.4 (\pm 2.3)$ ms
525 faster during Decision blocks than No Decision blocks [$t(1,23) = -5.52$, $p < 0.001$]. The
526 decrease in SRTs was similar for both Reaching and Interception [main effect of movement
527 type: $F(1,23) = 0.08$, $p = 0.79$, $\eta^2 < 0.01$], suggesting that adding a perceptual decision
528 increased the general urgency to launch a saccade. However, as can be seen for Interception
529 movements, there was likely a speed-accuracy trade-off associated with faster SRTs: the initial
530 saccade landed farther behind the moving object during Decision blocks [see Fig. 5C; main
531 effect of decision: $F(1,23) = 13.93$, $p = 0.001$, $\eta^2 = 0.04$] and for Fast trial durations (i.e., when
532 the object was moving at faster velocities) [main effect of trial duration: $F(1,23) = 37.25$, $p <$
533 0.001 , $\eta^2 = 0.07$]. Eye position lag persisted during approximately the first 300 ms of the
534 smooth-pursuit period [main effect of decision type: $F(1,23) = 17.74$, $p < 0.001$, $\eta^2 = 0.14$; main

535 effect of trial duration: $F(1,23) = 114.18, p < 0.001, \eta^2 = 0.32$]. This result suggests that the
 536 urgency of the initial saccade led to less precise oculomotor movement during decision-
 537 making.
 538



539 Figure 5: Perceptual decision-making influences eye movement strategies. A: Two representative trials showing classification
 540 of gaze events using adaptive velocity-based thresholds for reaching to stationary targets and intercepting moving targets. B:
 541 Saccadic reaction times decreased for Decision blocks similarly for reaching and interception. C: Gaze lag across interception
 542 trials for the end of the initial saccade and as a function of time from gaze onset. Positive values indicate that the gaze led the
 543 object, whereas negative values indicate lag. Participants lagged more during Decision blocks and at fast trial durations
 544 (higher object velocity). The error bars and shaded area represents the 95% confidence interval of the mean estimate. D:
 545 Gaze gain across interception trials as a function of time from gaze onset. Gaze gain was higher for faster velocities during the
 546 open-loop period and higher for Decision blocks during the closed-loop period. The shaded area represents the 95%
 547 confidence interval of the mean estimate. E: Distribution of catch-up saccades after gaze onset during interception. Catch-up
 548 saccades were more frequent during Decision blocks. The dotted lines denote the quartiles of the distribution.
 549

550 Participants compensated for the initial lag in pursuit by increasing the gaze gain.
 551 Though gaze gain in the open-loop period (15-100 ms after pursuit initiation) was driven mainly
 552 by differences in object velocity [main effect of trial duration: $F(1,23) = 58.67, p < 0.001, \eta^2 =$
 553 0.13], during the closed-loop period gaze gain increased for Decision blocks relative to No
 554 Decision blocks [main effect of decision: $F(1,23) = 49.02, p < 0.001, \eta^2 = 0.15$] (Fig. 5D). This
 555 effect is not simply due to longer pursuit durations during Decision blocks, as gains are also

556 longer when the analysis is restricted to the first 100 ms of the closed-loop period [main effect
557 of decision: $F(1,23) = 8.71$, $p = 0.007$, $\eta^2 = 0.04$]. This suggests that the negative closed
558 feedback loop that minimizes retinal error between gaze and target is engaged differently
559 when perceptual decision-making task-constraints are imposed during pursuit eye movements.

560 Participants also initiated more catch-up saccades during Decision blocks ($M = 0.99 \pm$
561 0.30 saccades/s) than No Decision blocks ($M = 0.68 \pm 0.30$ saccades/s) to make up for the lag
562 in object pursuit [main effect of decision type: $F(1,23) = 16.23$, $p < 0.001$, $\eta^2 = 0.10$] (see Fig.
563 5E). The mean latency of when the catch-up saccade occurred relative to pursuit onset did not
564 differ across decision type blocks [main effect of decision: $F(1,23) = 1.06$, $p = 0.31$, $\eta^2 < 0.01$]
565 or trial duration [main effect of trial duration: $F(1,23) = 2.25$, $p = 0.15$, $\eta^2 = 0.02$]. Together,
566 these results suggest that ocular movements are altered when decision about object features
567 have to be made in addition to estimating its spatial location.

568

569 Discussion

570 In the current study, we asked the question: how does perceptual decision-making
571 involving the two visual streams affect visuomotor coordination during reaching and
572 interception movements? To address this question, we manipulated ventral stream
573 involvement in a rapid visuomotor task. In one condition, participants made reaching or
574 interception movements to hit an object shaped like a circle. In another condition, participants
575 had to judge the shape of the object: if a circle appeared, they were instructed to reach or
576 intercept it, but if an ellipse appeared, they were instead instructed to make a movement away
577 from the ellipse and towards a horizontal bar. Our results support our first hypothesis of
578 differential effects of ventral stream engagement on dorsal stream processing during
579 interception relative to reaching movements. Furthermore, we also found support for our
580 second hypothesis - that changes in oculomotor behavior when the ventral visual stream is
581 engaged may contribute to differences in limb motor performance.

582 Many studies have probed the interactions between dorsal and ventral stream
583 processes during reaching movements (reviewed in Song and Nakayama 2009) but to the best
584 of our knowledge only a handful of studies have extended this type of paradigm to interception
585 movements (de la Malla et al. 2019; Lacquaniti and Maioli 1989). Our approach also differs
586 from the classical *backward masking* approach used by some researchers to quantify how
587 object recognition affects planning and execution of reaching movements (Cressman et al.
588 2007; Schmidt 2002). In this approach, a brief target stimulus (prime) is followed by a mask
589 that impedes recognition of the target. These studies showed that reaching movement
590 trajectories were strongly affected by the prime target, even when blocked from awareness by
591 masking, suggesting a flow of object property information from the ventral visual stream to the
592 dorsal action stream. In our approach, we presented the same stimulus for the entire trial
593 duration to afford participants flexibility in how they processed object shape. We chose two trial
594 times of 800 ms (Fast) and 950 ms (Slow) to give participants enough time to identify object
595 shape (~250-300 ms) and plan movements (~100-200 ms) in a sequential fashion, i.e. to
596 minimize decision errors participants could first ascertain the object shape and then plan the
597 movement trajectory. Our paradigm also allowed participants to judge the object shape and
598 prepare a motor plan simultaneously. If the slower ventral stream process of shape recognition
599 took longer than the preparation of the motor plan, we predicted that effective ventral-dorsal
600 stream integration would allow participants to take corrective action by completing shape
601 recognition after the movement had been initiated. Our results show that participants used

602 both strategies. Longer reaction times of ~500 ms were associated with fewer decision errors
603 and redirected movements (see Fig. 3C and 4C). In contrast, average reaction times of ~400
604 ms were associated with more decision errors as well as corrective redirected movements.

605

606 *Online integration of ventral stream and decision processing during interception*

607 Vision for goal selection based on object properties and vision guiding the online control
608 of movement have been conceptualized as two specialized processes mediated by the ventral
609 and dorsal streams, respectively (Goodale and Milner 1992; Goodale and Westwood 2004).
610 While much work has concerned how the two visual streams serve unique functional roles
611 operating largely independent of each other, less is known about the interaction in more
612 complex task environments. The current task was designed to force this interaction—that is, in
613 order to perform the correct action (hit the object or avoid it), participants must accurately
614 identify the object's shape (circle or ellipse). We found that even under time constraints (800
615 ms to hit the object in the Fast condition), participants could recognize objects and formulate a
616 decision prior to movement initiation. Relative to No Decision blocks, in which participants only
617 needed to process spatial information to facilitate movement, there was an average RT delay
618 of 178 ms in Decision blocks (see Fig. 3B), suggesting additional processing time for shape
619 recognition and motor goal selection (Cisek and Kalaska 2010; Thorpe and Fabre-Thorpe
620 2001; Veerman et al. 2008). Thus, it is reasonable to assume from the average RTs that
621 perceptual processing in the ventral stream could precede dorsal stream processing of
622 visuomotor transformations for action execution.

623 However, closer investigation of the movement trajectories and corresponding RTs
624 provides evidence that processing of object information and decision-making continues after
625 movement initiation. During both reaching and interception, we observed that participants
626 would often initiate their movements toward the circle only to curve around past the original
627 start location and hit the bar. The presence of these “redirect-to-avoid” movements (see Fig.
628 4D) provide evidence of an evolving decision given accumulating stimulus information (Resulaj
629 et al. 2009; Selen et al. 2012). In contrast to previous studies investigating sensorimotor
630 decisions of the limb that vary the motion or spatial location of the target (Burk et al. 2014;
631 Gallivan et al. 2016; van den Berg et al. 2016), here we show that sensorimotor
632 transformations computed in the dorsal stream can seamlessly integrate incoming information
633 about object shape that originates in the ventral stream (Davare et al. 2007; Konen and
634 Kastner 2008; Lehky and Tanaka 2016; Sereno and Maunsell 1998). The distribution of initial
635 movement directions (see Fig. 4E) of redirected movements toward the direction of the bar
636 suggests that movements are planned to optimize task success given uncertainty about the
637 impending decision (Haith et al. 2015; Nashed et al. 2017; Wong and Haith 2017). Thus, even
638 though the imposed time constraints allowed for sequential stimulus identification, decision-
639 making, and movement execution, participants tended to favor an alternative strategy in which
640 both these processes co-occurred during preparation and execution (Haith et al. 2016; Orban
641 de Xivry et al. 2017).

642 What determines the reliance on integration of ventral and dorsal stream information
643 during visuomotor control? In the present task, the complexity of the motor response
644 modulated the perceived urgency to act (Thura 2020; Thura and Cisek 2016). Both initial and
645 final decision errors increased during interception relative to reaching during decision-making,
646 largely due to participants initially aiming toward and then unable to correct a response toward
647 a moving ellipse. In addition, movements were more likely to be redirected during interception,

648 indicating a stronger bias toward initiating a hit movement prior to making a perceptual
649 decision about object shape. Furthermore, an individual's initial decision error rate and
650 tendency to perform redirect movements were each associated with shorter RTs, indicating
651 that the shorter RTs during interceptions in Decision blocks were likely due to a greater
652 dependency on online decision-making and motor control (Brenner and Smeets 2018).

653 However, given that the urgency to act during interception had clear consequences on
654 task performance (more decisional errors), the capacity for integration of ventral stream
655 information with visuomotor performance may be limited. Our results suggest that the urgency
656 of the response may interfere with, rather than be a consequence of, differential ventral-dorsal
657 stream interactions. Further work directly addressing different stimulus attributes associated
658 with separate areas along the ventral pathway (e.g., orientation, color, size) can help clarify
659 how movements are planned relative to the time-course of sensory processing and decision-
660 making. Notably, the errors in interception during decision-making were associated with the
661 inability to adjust initial movement trajectories that account for decisional demands, but the
662 increase in aiming errors was no different between interception and reaching. This suggests
663 that the interference in the time-course of ventral-dorsal stream interactions mainly affects
664 decision processes rather than the online control of movement per se.

665 Our study does not address how the dorsal stream receives ventral stream information
666 about object shape, but recent work has identified pathways between the two streams that
667 could facilitate direct communication during ongoing sensorimotor control (Budisavljevic et al.
668 2018; Takemura et al. 2016). The present findings suggest that that the motor system can
669 integrate prolonged processing of sensory information originating in the ventral stream, but
670 how the extent to which this integrated information can be accessed depends on movement
671 complexity.

672
673 *Modulation of gaze gains during perceptual decision-making*

674 During Decision blocks, saccades were launched about 10 ms earlier than No-Decision
675 blocks. It appears that the earlier launch of the saccade was because of a perceived urgency
676 to recognize the object shape and make the correct motor decision. Saccades to visible targets
677 are generally imprecise and undershoot target position (Krappmann 1998). Thus, the earlier
678 launch may have occurred before the spatial planning of the saccade was complete, resulting
679 in larger undershoots farther away from the object (larger gaze lags in Decision blocks, Fig.
680 5C). Since in our study objects had to be foveated to be recognized, the oculomotor system
681 may have increased the gaze gains (Fig. 5D) and made more catch-up saccades (Fig. 5E) to
682 the target during Decision blocks to compensate for the large lags at the end of the saccades.

683 Smooth-pursuit gains have been conventionally defined as the ratio of target and gaze
684 velocity in angular coordinates in head-fixed conditions. The first 100 ms of the smooth-pursuit
685 movement is referred to as the open-loop phase (Barnes 2008; Tychsen and Lisberger 1986).
686 This is followed by the onset of closed-loop pursuit, which is mainly controlled by a negative
687 feedback loop to ensure that the eye velocity closely matches the target velocity. However,
688 pursuit gains are defined for head-fixed conditions to ensure that the vestibular-ocular reflex
689 does not interfere with gaze movements. Since our eye-tracker could have allowed small head
690 movements, we decided to report gaze gains (Barnes 1993; Collins and Barnes 1999; Ranalli
691 and Sharpe 1988) instead of pursuit gains. One study in primates has shown that when the
692 head is unrestrained, pursuit and gaze gains are similar suggesting that eye and head
693 movements are controlled together within the pursuit pathways (Dubrovsky and Cullen 2002).

694 Thus, we compared both open-loop (first 100 ms) and closed-loop gaze gains (>100 ms) as a
695 proxy for pursuit gains for the Interception blocks for the No Decision and Decision conditions.

696 As expected, changes in the open-loop gains were driven predominantly by object
697 velocity (Fast versus Slow). However, the closed-loop gains were significantly higher for the
698 Decision than No Decision blocks. An important question is whether these higher gains for the
699 Decision blocks reflected the constraints imposed by shape recognition or were simply a
700 compensation for the large errors in where the saccade landed. Previously, it has been shown
701 that object recognition is impaired when targets move at high speeds (Ludvigh and Miller
702 1958b; Schütz et al. 2009; Westheimer and McKee 1975). In contrast to the slow speed of 1-
703 10°/sec used in these studies, the objects in our experiment moved at approximately 80-
704 90°/sec. This speed approaches the limit of smooth-pursuit in humans (Meyer et al. 1985) and
705 we expected that participants would not only have trouble in pursuing objects at high speeds,
706 but that it would also compromise their ability to recognize objects. However, the closed-loop
707 pursuit gains were similar between Fast and Slow blocks, and only differed between the
708 Decision blocks. Thus, it seems that the gaze lag (caused by earlier release of the saccade)
709 and the need to foveate the object to recognize the shape together contributed to a higher
710 closed-loop gaze gain. This suggests that the negative closed feedback loop that minimizes
711 retinal error between gaze and target is engaged differently when the ventral stream is
712 engaged for perceptual decision-making during pursuit eye movements.

713 Our result suggests that the visual perceptual decision-making network, that includes
714 the ventral visual stream, dorsolateral prefrontal regions and frontal eye fields (Heekeren et al.
715 2004; Heekeren et al. 2008; Sakagami and Pan 2007), may provide either a predictive or
716 urgency signal to the smooth-pursuit system to increase the gain and minimize the retinal error
717 between the target and the gaze. Indeed, stimulation and lesion studies have implicated the
718 frontal eye fields with the modulation of smooth-pursuit gain during object tracking (Gagnon et
719 al. 2006; Keating 1991; Morrow and Sharpe 1995; Shi et al. 1998). Furthermore, anatomical
720 tracer studies in primates have shown that the dorsal and ventral processing streams converge
721 in the lateral frontal eye fields (Schall et al. 1995). Taken together with our data, this suggests
722 that in tasks where perceptual decision-making is necessary during pursuit eye movements,
723 the frontal eye fields may modulate gaze gains to meet task demands.

724

725 *Conclusions*

726 In this study, we introduced a visuomotor decision-making task in which a successful
727 reaching or interception movement depended on visual processing for perception and action in
728 the ventral and dorsal streams. We found that engagement of the ventral stream led to more
729 decision errors and a smaller increase in hand RTs for interception movements relative to
730 reaching movements, reflective of a greater perceived urgency to act during interception.
731 During decision-making, participants had faster saccadic RTs and adopted online movement
732 strategies that incorporated an evolving decision about object shape. Additionally, participants
733 exhibited higher gaze gains to adapt to the demands of integrating the perceptual decision with
734 visuomotor control. These results suggest that the capacity to effectively integrate ventral-
735 dorsal stream information during ongoing movement depends on the perceived urgency to act,
736 which is greater when intercepting a moving target.

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