

1 Age-related increases in reaction time result from

2 slower preparation, not delayed initiation

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18 **Abstract**

19 Recent work indicates that healthy younger adults can prepare accurate responses faster
20 than their voluntary reaction times indicate, leaving a seemingly unnecessary delay of 80-100ms
21 before responding. Here we examined how the preparation of movements, initiation of
22 movements, and the delay between them are affected by ageing. Participants made planar
23 reaching movements in two conditions. The 'Free Reaction Time' condition assessed the
24 voluntary reaction times with which participants responded to the appearance of a stimulus. The
25 'Forced Reaction Time' condition assessed the minimum time actually needed to prepare
26 accurate movements by controlling the time allowed for movement preparation. The time taken
27 to both initiate movements in the Free Reaction Time and to prepare movements in the Forced
28 Response condition increased with age. Notably, the time required to prepare accurate
29 movements was significantly shorter than participants' self-selected initiation times; however, the
30 delay between movement preparation and initiation remained consistent across the lifespan
31 (~90ms). These results indicate that the slower reaction times of healthy older adults are not due
32 to an increased hesitancy to respond, but can instead be attributed to changes in their ability to
33 process stimuli and prepare movements accordingly, consistent with age-related changes in brain
34 structure and function.

35

36 **Introduction**

37 Adult human reaction times in response to simple tasks slow with age at a rate of 2-6ms
38 per decade (Fozard et al. 1994; Gottsdanker 1982; Woods et al. 2015). More complex tasks are
39 associated with greater reaction time differences between healthy young and old participants
40 (Woods et al. 2015). These increases in response times have been attributed to changes in both
41 the physical capabilities and the self-selected behaviors of older adults. Age-related changes in
42 brain physiology are associated with reductions in the speed of information processing (Seidler
43 et al. 2010). Compared to younger adults, older individuals have reduced grey matter volumes
44 (Giorgio et al. 2010), reductions in white matter integrity (Stadlbauer et al. 2008), and recruit
45 additional neural resources when completing tasks (Heuninckx et al. 2008), all of which could
46 contribute to slower sensorimotor processing times. A second factor that may contribute to this
47 decline comes from research suggesting that older adults take a more cautious approach when
48 performing tasks (Dully et al. 2018). For tasks in which performance is governed by a speed-
49 accuracy trade-off (Fitts 1954), younger adults appear to balance speed and accuracy in a way
50 that achieves a high rate of correct responses, while older adults reportedly focus on minimizing
51 errors at the cost of being slower (Salthouse 1979; Smith and Brewer 1995; Starns and Ratcliff
52 2010). It is unclear which of these explanations – slower processing or greater cautiousness – is
53 primarily responsible for the general increase in reaction times with ageing.

54 Cautiousness to respond (i.e. focusing on accuracy over speed) appears to occur even in
55 tasks that one might expect to be highly reactive, such as reaching to a visual target. We have
56 recently shown that healthy younger adults can detect a target location and prepare an accurate
57 movement in as little as 150ms, but introduce a delay of 80-100ms before voluntarily initiating a
58 response (Haith et al. 2016), seemingly to avoid committing errors in which responses were
59 initiated before they had been prepared. Here our goal was to quantify the effects of aging on
60 movement preparation, movement initiation, and the relationship between them. We

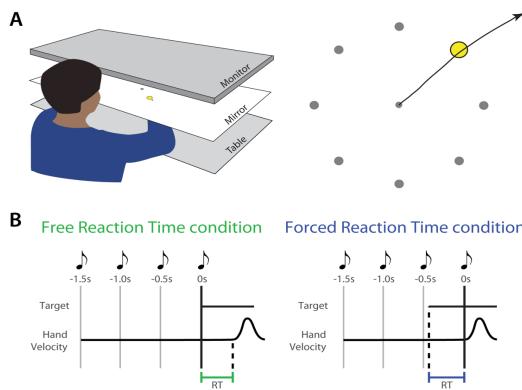
61 hypothesized that if healthy older adults delay their actions in order to favor accuracy, the delay
62 between the minimum time required to prepare movements and the time at which they are
63 voluntarily initiated may increase with age.

64 In the present study we therefore examined the extent to which the slower reaction times
65 of healthy older individuals are due to a slowing of their ability to process perceptual information
66 and prepare appropriate movements (i.e. due to an overall reduction in processing speed), and/or
67 an increase in the delay between when their movements are prepared and initiated (e.g. favoring
68 accuracy over speed to avoid the risk of making an error). Participants completed a planar
69 reaching task, and their reaction times were measured in two different conditions. The 'Free
70 Reaction Time' condition (equivalent to standard "choice reaction time" testing), assessed the
71 time at which participants would voluntarily initiate movements in response to the appearance of
72 a target. The 'Forced Reaction Time' condition, based on an established psychophysics paradigm
73 (Ghez et al. 1997; Haith et al. 2015a, 2015b, 2016; Hardwick et al. 2019), forced participants to
74 respond at lower-than-normal reaction times, allowing us to determine the amount of time they
75 needed to prepare accurate responses. Our results indicate that the time participants required to
76 both initiate and prepare responses increased with age; however, the delay between preparation
77 and initiation of movements remained invariant at around 90ms. These results indicate that the
78 slower reaction times of healthy older adults observed in this task were not due to an increased
79 hesitancy to respond, but can instead be wholly attributed to declines in the ability to process
80 stimuli and prepare accurate movements.

81

82 Methods

83 54 human participants aged between 21-80 completed the study (see Table 1 for summary
84 data). Previous research indicates typical correlations between age and reaction time in the range
85 of $r=0.46$ to $r=0.51$ (Bugg et al. 2006; Woods et al. 2015). Power analysis based on the more
86 conservative $r=0.46$, with 80% power and a two-tailed alpha of 0.05 indicated that a sample of 35
87 participants would be sufficient to detect effects in the present study (based on power analysis
88 calculations from Hulley 2007). All participants had no known neurological disorders and had
89 normal cognition (a score of ≥ 26 on the Montreal Cognitive Assessment (Nasreddine et al. 2005).
90 All participants provided written informed consent prior to their participation, and all procedures
91 were approved by the Johns Hopkins University School of Medicine Institutional Review Board.



93 *Figure 1: Apparatus and Experimental Conditions. A) Participants made planar reaching*
94 *movements to interact with an on-screen display. Participants made ballistic 'shooting' actions*
95 *with the goal of passing the cursor through a target. The target appeared in one of eight locations.*
96 *B) Experimental conditions. In the Free Reaction Time condition the target appeared at a fixed*
97 *time cued by a sequence of tones. Participants attempted to respond by initiating a movement as*
98 *soon as possible. In the Forced Reaction Time condition participants always initiated movements*
99 *at a fixed time (synchronously with the final tone in a sequence of four). The target appeared at a*
100 *random time prior to movement; the time between target presentation and the fourth tone*
101 *therefore imposed a limited response time.*

102 **Apparatus**

103 Participants sat at a glass-surfaced table with their dominant arm supported by an air sled,
104 allowing frictionless 2D movements in the horizontal plane (see Figure 1). A monitor and mirror
105 setup allowed presentation of visual targets in the same plane as the arm. Hand position was
106 tracked at 130Hz using a Flock of Birds motion tracking system (Ascension Technologies).

107 Participants moved their hand to control the position of a cursor (blue circle, 5mm
108 diameter). Each trial began with the cursor in a central start position (green circle, 10mm
109 diameter). The two experimental conditions (Free and Forced Reaction Time - see below)
110 required participants to make a ballistic arm movement (i.e. movements that use feedforward
111 control with little opportunity to make online corrections to their movement; (Hardwick et al. 2013)
112 with the goal to pass the cursor through a target (grey circle, 25mm diameter). The target could
113 appear in one of eight locations, each spaced equally around the start position at a distance of
114 80mm.

115 **Free Reaction Time Condition**

116 Participants were instructed to react as quickly as possible to the appearance of a target.
117 The timing of stimulus presentation was predictable, occurring synchronously with the final tone
118 in a sequence of four equally spaced tones (500ms separation). This cuing reduced ambiguity
119 regarding the timing of stimulus presentation, which reduces reaction times and their variability
120 (Frith and Done 1986). Participants completed 1-4 blocks (each 96 trials) of Free Reaction Time
121 trials (the number of blocks varied depending on the time available to test the participant). The
122 targets appeared in a pseudorandom sequence, with each target appearing 12 times per block.

123

124 **Forced Reaction Time Condition**

125 The Forced Reaction Time condition used an established paradigm that requires
126 participants to respond at a prescribed time within each trial (Ghez et al. 1997; Haith et al. 2015a,
127 2015b, 2016; Hardwick et al. 2019). Participants heard a sequence of four equally spaced tones
128 (500ms separation), and were trained to initiate their movements synchronously with the onset of
129 the fourth and final tone. Different reaction times were imposed by varying the time at which the
130 target was presented relative to the required time of movement onset. Participants were instructed
131 that while both the timing and the accuracy of their movements was important in this condition,
132 their highest priority was to attempt to begin their response synchronously with the fourth tone. If
133 participants failed to initiate their movement within +/-75ms of this time, on-screen feedback
134 informed them that they were "Too early" or "Too late". If participants failed to time their movement
135 accurately on three consecutive trials the experimenter also provided additional feedback,
136 reiterating the instruction that accurate timing was their highest priority in this condition. Analyses
137 accounted for discrepancies in participant timing (i.e. differences in time between participants
138 responses and the fourth tone) in several ways. First, we determined the 'actual' time participants
139 used in each trial by measuring the time between the onset of the stimulus and their response
140 (rather than the experimentally 'prescribed' time based on the time between stimulus onset and
141 the fourth tone). Secondly, a set of 'asynchrony' analyses examined differences in timing between
142 the participant responses and the fourth tone.

143 In initial training blocks the target appeared at the onset of the trial, allowing the participant
144 1500ms to prepare a response. Participants trained for one block of 50 trials; if they could
145 accurately time the initiation of their movement in at least 35/50 trials they proceeded to the main
146 experiment, otherwise they completed a second 50-trial training block. Participants then
147 completed trials with variable target presentation times. In each block, target presentation varied
148 uniformly between 0 and 400ms prior to the fourth tone (if participants failed to produce correct

149 responses within this time window the range was increased to 600ms). Each block began with
150 two 'warm up' trials in which the target appeared with the first tone. Participants completed 2-4
151 blocks (106 trials each) of Forced Reaction Time trials (the variable number of blocks depended
152 on the time available to test the participant and their adherence to instructions).

153 ***Data Analysis***

154 Hand position was processed with a second order Savitzky-Golay filter (half-width 54ms).
155 Movement onset was calculated as the time at which tangential hand velocity first exceeded
156 0.02m/s. We subtracted the mean delay in the recording system (measured to be 100ms) to
157 provide a more accurate measure of true reaction time. Reaction time in both the Free Reaction
158 Time and Forced Reaction Time conditions was calculated as the delay between the onset of the
159 stimulus and movement onset. Initial movement direction was calculated from the direction of the
160 hand's velocity 100ms after movement onset.

161 Data from the Forced Reaction Time condition was used to model the probability of
162 initiating an accurate movement at a given reaction time (i.e. a speed-accuracy trade-off) based
163 on a previously established approach (Haith et al. 2016; Hardwick et al. 2019). Movements were
164 considered to have been initiated in the correct direction if the initial movement direction was
165 within 22.5° of the target. For data visualization purposes, the proportion of movements initiated
166 in the correct direction was calculated for a 20ms sliding window around each potential reaction
167 time. For analysis, a speed-accuracy trade-off was modeled as a cumulative Gaussian distribution
168 centered on time T_p (thus $T_p \sim N(U_p, \sigma_p^2)$). This assumes movements before T_p were directed
169 randomly with respect to the true target location, while movements after T_p were initiated in the
170 correct direction with some probability α . Parameters were estimated from the data for each
171 individual participant using a maximum likelihood approach.

172 Statistical analyses were conducted using JASP (0.13.1.0). The relationship between
173 movement preparation and initiation was analyzed using a repeated-measures ANOVA
174 (_{RM}ANOVA). The _{RM}ANOVA assessed the within-subjects factor of Time - Initiation Time
175 (calculated using the Free Reaction Time condition) was compared to Preparation Time
176 (calculated using the Forced Reaction Time condition), with Age included as a covariate. Further
177 correlation and regression analyses assessed whether Age affected Initiation Time, Preparation
178 Time, or the delay between them (i.e. Initiation Time minus Preparation Time). Data submitted to
179 correlation analyses were screened for outliers using the "Robust Correlation" MATLAB toolbox
180 (Pernet et al. 2013). This toolbox provides an objective approach to identifying and removing
181 outliers without loss of statistical power. Where outliers were identified we report the 'Skipped'
182 Pearson correlation (calculated by removing outliers and determining the correlation for the
183 remaining datapoints), which directly reflects Pearson's *r* (Pernet et al. 2013). Note that the
184 inclusion/removal of outliers did not change any of our empirical results. Where appropriate,
185 additional Bayesian analyses were conducted to determine the level of evidence in support of the
186 null hypothesis (BF_{01}), with classifications according to Wagenmakers et al. 2011. In the Bayesian
187 analyses, outliers were removed based on the Robust Correlation procedure outlined above.
188 Again, the inclusion/removal of outliers did not change any of our empirical results.

189 A series of control analyses examined the effects of the different experimental conditions,
190 and participant age, on behavior. We first conducted correlation and regression analyses to
191 determine whether participants completed the Free and Forced Reaction Time conditions with
192 similar peak movement velocities. Possible differences were considered in a _{RM}ANOVA
193 comparing peak movement velocity across conditions (Free vs Forced Reaction Time conditions),
194 including Age as a covariate. Additional correlation and regression analyses considered the
195 relationship between participant Age and peak movement velocity in the Free and Forced
196 Reaction Time conditions. Further analyses examined possible effects of Age on participant

197 behavior in the Forced Reaction Time condition. Possible effects of Age on asymptotic accuracy
198 (identified based on the model fit to the data for each participant) were examined using correlation
199 and regression analyses. Possible effects of Age on timing accuracy were also assessed;
200 Response Asynchrony was calculated as the difference in time between the fourth tone and the
201 start of the participant's response (Vleugels et al. 2020). Negative values therefore corresponded
202 to moving before the fourth tone, and positive values corresponded to moving after the fourth
203 tone. Correlation and regression analyses then assessed the possible relationship between Age
204 and both signed and absolute Response Asynchrony.

205 All regression analyses are presented with bootstrapped 95% confidence intervals,
206 calculated using resampling with replacement (Hardwick and Celnik 2014). A linear model was fit
207 to each resampled population, and a line of best fit was then interpolated from the model
208 parameters. This process was repeated 10,000 times, with the 2.5 and 97.5 percentiles of the
209 interpolated fits being used as confidence intervals.

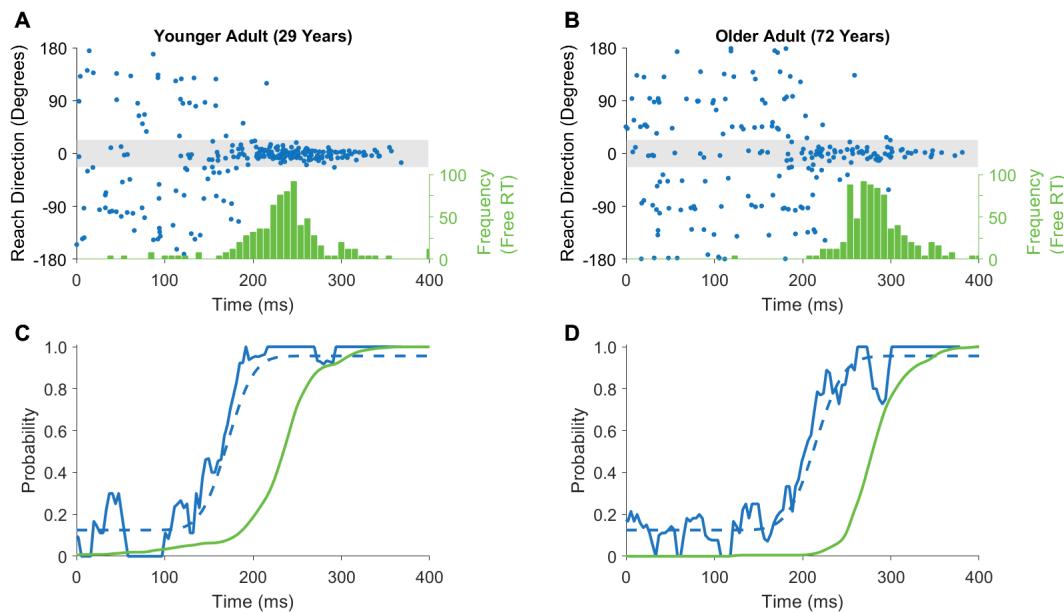
210 **Results**

Age	Sex	Hand	Initiation Time (Mean \pm SD, ms)	Mean PT (ms)	Difference (IT - PT)	Accuracy (Free RT, %)
21	F	R	355 \pm 43	264	91	95.3
21	F	R	399 \pm 36	280	119	99.0
21	F	R	387 \pm 27	283	104	100.0
21	F	L	364 \pm 38	292	72	99.7
21	F	R	420 \pm 47	304	116	100.0
23	M	R	380 \pm 32	305	75	99.2
24	M	R	368 \pm 36	289	79	98.7
25	F	R	346 \pm 49	238	108	99.3
28	M	R	370 \pm 29	268	102	100.0
28	F	R	387 \pm 31	275	112	96.9
29	M	R	344 \pm 27	253	91	99.7
29	F	L	328 \pm 55	271	57	99.0
29	M	R	403 \pm 29	271	132	99.5
30	F	R	329 \pm 24	255	74	100.0
31	F	R	398 \pm 31	294	104	99.5
34	M	R	354 \pm 28	294	60	99.5
35	M	R	339 \pm 20	265	74	99.5
36	F	R	400 \pm 82	286	114	100.0
36	F	R	404 \pm 53	327	77	98.2
37	F	R	435 \pm 38	303	132	98.4
38	F	R	391 \pm 37	315	76	99.7
40	F	L	395 \pm 36	281	114	99.2
40	M	R	411 \pm 59	302	109	97.9
42	F	R	411 \pm 39	293	118	100.0
43	F	R	352 \pm 41	291	61	100.0
44	F	R	370 \pm 41	309	61	98.4
45	F	R	429 \pm 31	328	101	99.0
45	M	R	480 \pm 17	339	141	99.5
47	F	R	380 \pm 48	300	80	98.4
50	F	R	404 \pm 42	325	79	96.4
55	F	R	444 \pm 35	288	156	98.7
56	F	R	370 \pm 42	270	100	99.7
56	F	R	327 \pm 37	288	39	100.0
56	M	R	421 \pm 42	338	83	99.7
57	F	R	394 \pm 77	284	110	96.5
57	F	R	372 \pm 39	289	83	99.0
58	M	R	411 \pm 34	309	102	96.9
59	F	R	429 \pm 40	278	151	99.5
59	F	R	379 \pm 35	321	58	99.0
59	M	R	362 \pm 69	323	39	100.0
61	F	R	378 \pm 30	299	79	94.5
62	F	L	431 \pm 29	298	133	99.5
62	M	R	361 \pm 35	305	56	99.2
63	M	R	439 \pm 35	299	140	98.7
66	F	R	351 \pm 44	228	123	100.0
68	M	R	384 \pm 34	282	102	99.5
70	F	L	468 \pm 33	382	86	100.0
71	F	R	379 \pm 41	294	85	100.0
72	M	R	381 \pm 45	294	87	98.7
72	M	R	386 \pm 38	314	72	99.0
72	F	R	383 \pm 34	315	68	99.0
72	M	L	397 \pm 42	326	71	96.4
76	F	R	400 \pm 54	301	99	97.9
80	M	R	453 \pm 32	325	128	100.0
Summary	Mean \pm SD	Count	Count	Mean \pm SD	Mean \pm SD	Mean \pm SD
	46.9 \pm 17.6	35F,19M	48R, 6L	390 \pm 35ms	295 \pm 26ms	98.9 \pm 1.3%

211

212 **Table 1:** Test population summary data

213 **Initiation time and preparation time dissociate**

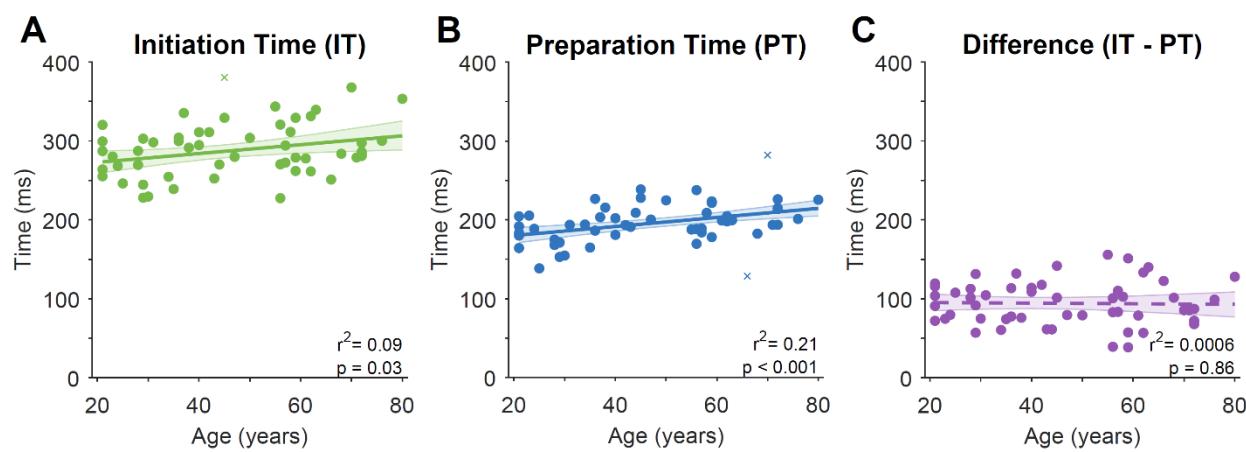


215 *Figure 2: Data from example participants. Upper panels (A-B) show the distribution of reaction*
216 *times in the Free Reaction Time condition (green histogram) and responses from individual trials*
217 *in the Forced Reaction Time condition (blue dots). Responses falling within the grey shaded area*
218 *were initiated in the correct direction. Lower panels (C-D) show a processed version of the data*
219 *for the subject above. The solid green lines present a cumulative distribution of reaction times*
220 *from the Free Reaction Time condition. Blue lines present data from the Forced Reaction Time*
221 *condition; solid blue lines show a sliding window of successful responses, while dashed blue lines*
222 *represent model fit to the data based on a cumulative Gaussian.*

223 In line with our previous work, we found a significant difference between Initiation Time,
224 as measured using the Free Reaction Time condition, and Preparation Time, as measured using
225 the Forced Reaction Time condition, $F_{1,52}=77.7$, $p<0.001$ (see Figure 2 for example data).
226 Participants' reaction times were significantly longer than the time they needed to prepare an
227 accurate action in the Forced Reaction Time condition ($t=24.82$, $p<0.01$, mean Initiation Time
228 (Free Reaction Time condition) = 290 ± 34 ms, mean Preparation Time (Forced Reaction Time
229 condition) = 195 ± 26 ms, mean difference = 94 ± 28 ms).

230 **Both initiation time and preparation time increase with age**

231 While Age was not a significant covariate in the RMANOVA for within-subject comparisons
232 of Reaction and Preparation Times ($F_{1,52}=0.032$, $p=0.86$), between-participants comparisons
233 indicated that response times increased significantly with Age ($F_{1,52}=8.0$, $p=0.007$). Further
234 analyses assessed the correlation between Age, Reaction Time, and Preparation Time.
235 Replicating the findings of previous research, we found that increased age was related to a
236 significant increase in reaction times in the Free Reaction Time condition (1 outlier removed,
237 Skipped Pearson's $r=0.30$, $p=0.03$; Figure 3A). Analysis of data from the Forced Reaction Time
238 condition also revealed that movement preparation time increased significantly with Age (2
239 outliers removed, Skipped Pearson's $r=0.45$, $p=0.0007$; Figure 3B). Accuracy in the Free
240 Response condition high for all participants (mean $98.9\pm1.3\%$), and analysis indicated there was
241 no significant correlation between accuracy and age ($r=-0.08$, $p=0.56$). Further Bayesian
242 correlation analysis found substantial evidence for the null hypothesis ($BF_{01}=5.0$), indicating that
243 performance in the Free Response condition was close to ceiling for all participants, regardless
244 of their age.

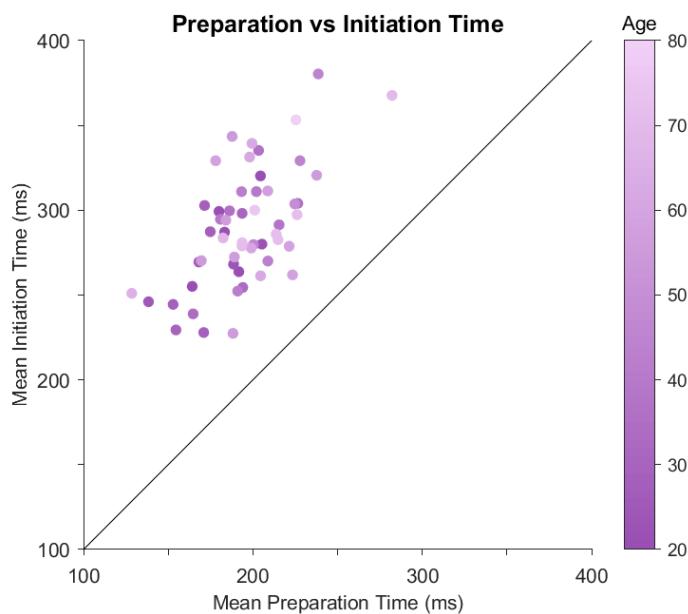


246 *Figure 3: Relationships between Age and movement Initiation Time (Free Reaction Time
247 condition), Preparation Time (Forced Reaction Time condition), and the delay between movement*

248 *Preparation and Initiation. Each point presents data from a single subject (crosses indicate*
249 *outliers as identified by robust correlation analysis, which were not included in summary*
250 *statistics). Solid line presents linear regression on the data, dashed lines present non-significant*
251 *regression lines. Error bars present bootstrapped 95% confidence intervals.*

252 **Age does not affect the delay between movement preparation and initiation**

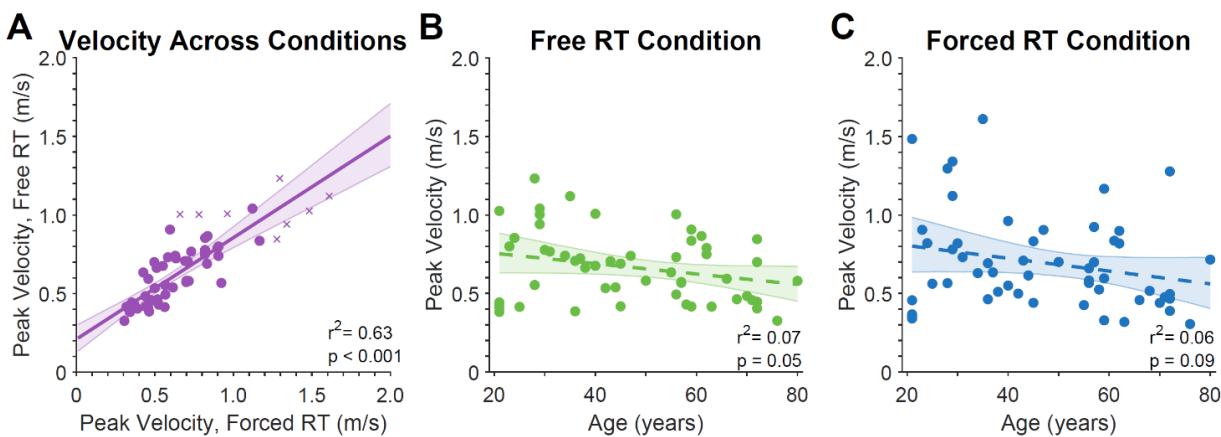
253 The delay between movement preparation and initiation was calculated for each
254 participant by taking their mean reaction time, as established in the Free Reaction Time condition,
255 and subtracting their mean preparation time, established based on the speed-accuracy trade-off
256 observed in the Forced Reaction Time condition (Figure 4). As identified in an earlier analysis, all
257 participants exhibited a delay between movement Preparation and Initiation (mean \pm SD =
258 94 \pm 28ms). There was, however, no significant relationship between age and the duration of the
259 delay (Figure 3C, Pearson's r =-0.025, p =0.86). Further analysis using Bayesian correlation
260 indicated there was substantial support for the null hypothesis ($BF_{01} = 5.801$) (Wagenmakers et al.
261 2011).



263 *Figure 4: Preparation Time vs Initiation Time. Each circle represents one participant, with lighter*
264 *colors presenting increasingly older participants. Note that each participant's Initiation Time*
265 *(average of reaction times for that participant in the Free Reaction Time condition) was greater*
266 *than their Preparation Time (average time of response preparation based on a model fit to data*
267 *for that participant in the Forced Reaction Time condition).*

268 **Peak movement velocity was correlated across conditions and decreased with age**

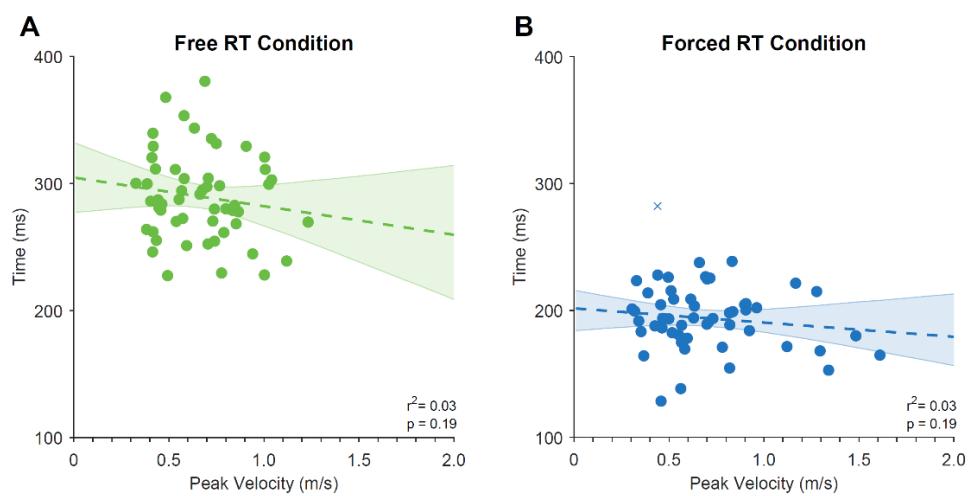
269 Control analyses examined whether peak movement velocity affected performance within
270 and across conditions. Participant peak movement velocity in the Free and Forced Reaction Time
271 conditions was highly correlated (8 outliers removed, Skipped Pearson's $r = 0.79$, $p=5.7916e-11$
272 Figure 5A). A corresponding $_{RM}$ ANOVA found no significant difference between peak movement
273 velocity in the Free and Forced Reaction Time conditions ($_{RM}$ ANOVA, $F_{1,52}=0.87$, $p=0.36$),
274 suggesting participant movement speeds were consistent between the two conditions. As older
275 age is associated with slower movement speeds, we also examined whether peak movement
276 velocity differed with Age. Age was not a significant covariate in the $_{RM}$ ANOVA ($F_{1,52} =0.31$,
277 $p=0.58$), but the analysis indicated a trend for Age as a between-subjects effect on peak velocity
278 ($_{RM}$ ANOVA, $F_{1,52}=3.7$, $p=0.06$). Correlation analyses suggested that peak velocities increased with
279 age, with trends for this effect in both the Free Reaction Time condition (Pearson's $r=-0.26$,
280 $p=0.055$; Figure 5B) and Forced Reaction Time condition (Pearson's $r=-0.24$, $p=0.088$; Figure
281 5C).



283 *Figure 5: Analyses of peak velocity. Left panel shows correlation between Peak velocity in the*
284 *Free and Forced Reaction Time conditions. Central and Right panels show correlations between*
285 *peak velocity and age in the Free and Forced Reaction Time conditions, respectively. Each point*

286 *presents data from a single subject (crosses indicate outliers as identified by robust correlation*
287 *analysis, which were not included in summary statistics). Solid line presents linear regression on*
288 *the data, dashed lines present non-significant regression lines. Error bars present bootstrapped*
289 *95% confidence intervals.*

290 Further analysis examined whether differences in movement speed across ages might have
291 accounted for the observed differences in preparation time and initiation time. We found no
292 significant relationship between reaction time and peak velocity in the Free Reaction Time
293 Condition (Pearson's $r=-0.14$, $p=0.30$; Figure 6A), or the Forced Reaction Time Condition (1
294 outlier removed, Skipped Pearson's $r=-0.18$, $p=0.19$, Figure 6B). Bayesian analysis indicated
295 there was substantial support for the null hypothesis when comparing reaction time and peak
296 velocity in the Free Reaction Time condition ($BF_{01}=3.5$), and anecdotal evidence for the null
297 hypothesis in the Forced Reaction Time condition ($BF_{01}=2.6$).



299 *Figure 6: Comparisons of peak velocity and reaction time for the Free Reaction Time condition*
300 *(A) and Forced Reaction Time (B) conditions. Each point presents data from a single subject*
301 *(crosses indicate outliers as identified by robust correlation analysis, which were not included in*
302 *summary statistics). Dashed lines present non-significant regression lines. Error bars present*
303 *bootstrapped 95% confidence intervals.*

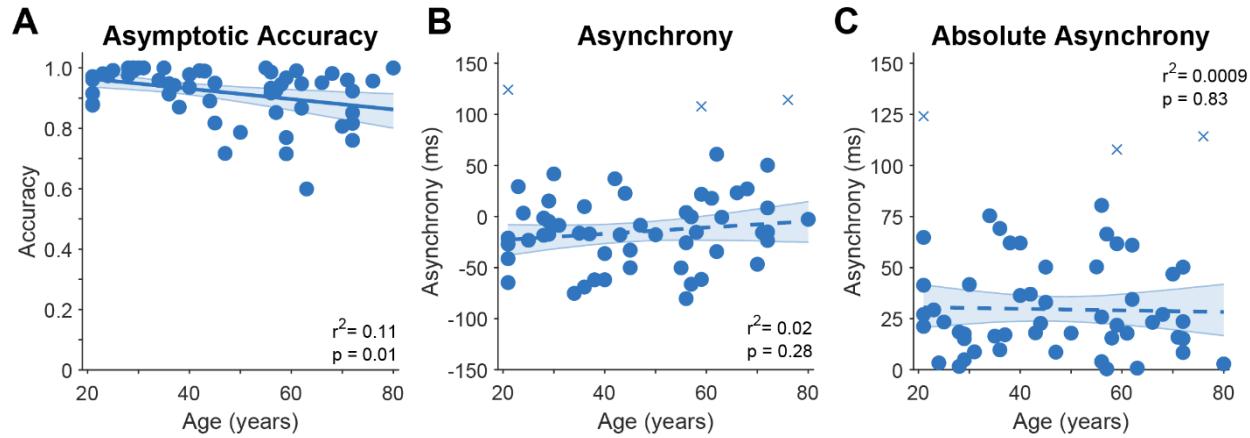
304 ***Asymptotic accuracy in the Forced Reaction Time condition decreased with age***

305 A correlation analysis indicated that asymptotic accuracy in the Free Reaction Time
306 condition decreased significantly with age ($r=-0.34$, $p=0.012$; see Figure 7A). This decline
307 occurred at a relatively low rate (0.0017% decrease in accuracy per year), corresponding to an
308 approximate decrease of 11% from ages 20 to 80 (97% vs 86% accuracy, respectively).

309

310 ***Timing (Asynchrony) in the Forced Reaction Time condition did not differ with age***

311 A final analysis examined participant's ability to time their responses in the Forced
312 Reaction Time condition to coincide with the fourth tone. Signed response Asynchrony did not
313 differ significantly with age (Pearson's $r=0.15$, $p=0.29$, 3 outliers removed, Skipped Pearson's
314 $r=0.16$, $p=0.28$: See Figure 7B), and Bayesian analysis provided substantial evidence in support
315 of the null hypothesis ($BF_{01}=3.2$; Wagenmakers et al. 2011). Absolute response Asynchrony also
316 did not differ with age (Skipped Pearson's $r=-0.03$, $p=0.83$), with further Bayesian analysis again
317 providing substantial support for the null hypothesis ($BF_{01}=5.6$). Together these analyses suggest
318 that timing asynchrony in the forced response condition did not differ significantly with age.



320 *Figure 7: Effects of Age on behavior in the Forced Reaction Time condition. Left panel indicates*
321 *the significant relationship between Age and Asymptotic Accuracy. Right panel indicates the non-*
322 *significant relationship between Age and Response Asynchrony. Each point presents data from*
323 *a single subject (crosses indicate outliers as identified by robust correlation analysis, which were*
324 *not included in summary statistics). Solid line presents linear regression on the data, dashed lines*
325 *present non-significant regression lines. Error bars present bootstrapped 95% confidence*
326 *intervals.*

327 **Discussion**

328 We used a visually-guided planar reaching task to measure reaction times and assess the
329 time participants needed to prepare accurate movements. In line with previous studies, we found
330 that 'Free' reaction times increased linearly with age (Fozard et al. 1994; Gottsdanker 1982;
331 Woods et al. 2015). We compared these data to performance in a 'Forced Reaction Time'
332 condition, in which we measured the minimum time participants required to prepare accurate
333 movements by forcing them to respond with shorter-than-normal response times. The time
334 required to prepare accurate movements also increased linearly with age, and was significantly
335 shorter than the reaction time, replicating our previous observation that movements are not
336 immediately initiated once they are prepared (Haith et al. 2016). Further analysis identified that
337 age had no significant effect on the delay between movement preparation and initiation. These
338 results indicate that the slower reaction times of healthy older adults observed in this task were
339 not due to an increased hesitancy to respond, but can instead be wholly attributed to declines in
340 the ability to process stimuli and prepare accurate movements.

341 Healthy human aging is associated with changes in motor behavior including declines in
342 coordination, increased kinematic variability, and a reduced ability to modify movements to
343 respond to changes in the environment (Hardwick and Celnik 2014; Sarlegna 2006). Such age-
344 related changes in behavior are accompanied by changes in brain structure and function (Dully
345 et al. 2018; Heuninckx et al. 2008; Stadlbauer et al. 2008). The increase in the amount of time
346 required to prepare movements with age, as identified here, is consistent with these previous
347 findings. Previous work has also suggested that healthy older adults prefer to respond with longer
348 reaction times to ensure accurate responses (Salthouse 1979; Smith and Brewer 1995; Starns
349 and Ratcliff 2010). Here we found no evidence of such age-related delays in responding. We note,
350 however, that the simple reaching task used here had relatively low cognitive demands. Age-
351 related declines in performance are exacerbated by increased task complexity and/or greater

352 cognitive demand (Woods et al. 2015), consistent with frequently demonstrated differences
353 between cognitive and motor functions (Wollenweber et al. 2014; Wu et al. 2004). We therefore
354 propose that the reported delaying of action in those studies may not represent a 'default policy'
355 for older adults, but could instead occur in response to increases in task complexity.

356 Further analyses indicated that increasing age was associated with slower peak
357 movement velocities in all conditions, and decreases in asymptotic accuracy in the Forced
358 Reaction Time condition. This drop in accuracy may have reflected an increased propensity for
359 lapses in concentration, particularly given the dual demands of timing and accuracy in the Forced
360 Reaction Time condition. Skilled motor performance is characterized by both speed and accuracy
361 (Hardwick et al. 2017; Rajan et al. 2019; Reis et al. 2009; Shmuelof et al. 2012, 2014), and the
362 present data are consistent with aforementioned and well-established age-related declines in
363 movement control. By contrast, there was no significant effect of age on the ability to synchronize
364 responses with the fourth tone, as evidenced by the analysis of Response Asynchrony in the
365 Forced Reaction Time condition. Note, however, that this does not necessarily reflect
366 spontaneous, self-selected participant behavior. Instructions to participants in the Forced
367 Reaction Time condition emphasized that while both the accuracy and timing of their responses
368 were important, timing was the highest priority. Older adults may have had greater asynchrony
369 (due to a tendency to delay their movements to wait for the target to appear, so they could reach
370 in the correct direction) without this intervention. We therefore conclude that increasing age was
371 associated with a decrease in overall performance (i.e. older adults had longer Initiation Times,
372 longer Preparation Times, lower peak movement velocities, and were less accurate).

373 In summary, our results are consistent with previous observations that humans delay the
374 initiation of prepared movements, and show that the size of this delay remains constant across
375 the lifespan. The consistent duration of this delay indicates that healthy older adults do not appear
376 to change their behavior in relatively simplistic response time tasks in order to favor accuracy at

377 the expense of speed. The declines in their performance observed here can instead be wholly
378 attributed to age-related changes in their capability to process and prepare movements.

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385

386 **Author Contributions**

387 RMH conceived the research. RMH, AF, and MGC collected the data. RMH analyzed the data.
388 RMH drafted the manuscript. RMH, AF, MGC, KZ and AH revised the draft.

389

390 **Additional Information**

391 The authors declare no competing interests.

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393 **Data Availability**

394 The datasets generated during and/or analyzed during the current study are available from the
395 corresponding author on reasonable request.

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