Quantitatively Assessing Aging Effects In Rapid Motor Behaviours: A Cross-Sectional Study

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RESEARCH

Quantitatively assessing aging effects in rapid motor behaviours: a cross-sectional study

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Abstract

Background: An individual's rapid motor skills allow them to perform many daily activities and are a hallmark of physical health. Although age and sex are both known to affect motor performance, standardized methods for assessing their impact on upper limb function are limited.

Methods: Here we perform a cross-sectional study of 618 healthy human participants in two interactive motor tasks developed to quantify sensorimotor abilities, Object-Hit (OH) and Object-Hit-and-Avoid (OHA). The tasks required participants to hit virtual objects with and without the presence of distractor objects. Velocities and positions of hands and objects were recorded by a robotic exoskeleton, allowing motor and cognitive parameters to be calculated for each trial. We verified that these tasks are viable for measuring performance in healthy humans and we examined whether any of the motor or cognitive parameters were related to age or sex.

Results: Our analysis shows that both OH and OHA can assess rapid motor behaviours in healthy human participants. It also shows that cognitive parameters in these tasks decline with age, while motor parameters do not. Three cognitive parameters show significant sex-related effects in OH, but these effects disappear in OHA.

Conclusions: This study suggests that the underlying effect of aging on rapid motor behaviours is not on the motor system per se, but on the brain's processing rate. Additionally, this study provides a baseline description of healthy human performance in OH and OHA when using these tasks to investigate age-related declines in sensorimotor ability.

Keywords: Rapid motor behaviour; Sensorimotor system; Aging; Robotic assessment

¹Background

² The ability to perform rapid motor behaviours underpins our interactions with the world, e.g.,
³ driving a car, dancing with a partner, or simply reacting when bumped walking in a crowded shop-
⁴ ping mall. In recognition of their importance to our daily lives, motor skills have been incorporated
⁵ into a number of neuropsychological tests, assessing individuals for cognitive and sensorimotor im-
⁶ pairments [1, 2, 3]. Unfortunately, motor abilities predictably decline with age and these declines
⁷ eventually limit many individuals' independence [4]. With the world projected to have two billion
⁸ people aged 60 or over by 2050, [5], there is a powerful motivation to measure the effects of aging
⁹ on the motor system.

¹¹ Aging impacts individuals' motor abilities in a number of ways, including: reducing muscle
¹² strength [6, 7, 8], reducing visuomotor adaptation [9, 10], worsening reach-to-grasp movements [11],
¹³ declining motor imagery abilities [12], decreasing accuracy in bimanual movements [13], increasing
¹⁴ perception of physical fatigue [14], and decreasing proprioceptive acuity [15, 16, 17]. There is also
¹⁵ evidence that aging has different impacts on various regions in male and female brains [18, 19, 20]
¹⁶ and that there are sex-related differences in sensorimotor skill as well [15, 21],

¹⁷ Confoundingly, there is also evidence that some characteristics of the sensorimotor system are
¹⁸ resilient to age, such as the mechanical properties of the elbow [22], the ability to perform complex
¹⁹ motor actions [23, 24], the ability to act without visual feedback [25, 26], and grip strength when
²⁰ fatigued [27]. This points to the difficulty in deciding how declines in motor abilities due to age will
²¹ affect daily activities at the population-level, let alone for a given individual.

²² Therefore, there is a clear need for tests that provide a holistic view of age-related declines in motor
²³ abilities. There has been a recent proliferation of rapid motor behavioural tasks with interactive
²⁴ components. To date these tasks have been used to quantify impairments after stroke [28, 29],
²⁵ to study decision-making [30, 31], and to study planning [32], but they also hold the promise of
²⁶ assisting research into the effects of age and sex on sensorimotor skills. Understanding how motor
²⁷ behaviours change with age in these interactive settings will help to develop new neuropsychological
²⁸ tests and equipment to evaluate an individual's ability to perform every day rapid motor actions.

The purpose of this study is to better understand the effects that age and sex have on an individual's rapid motor skills. To achieve this we use two interactive motor behaviour tasks, namely Object-Hit (OH) [28] and Object-Hit-and-Avoid (OHA) [29], which are performed in a robotic exoskeleton to permit the recording of upper limb and joint positions throughout trials. We verify that these tasks are appropriate for testing healthy individuals by demonstrating that participants must reach and maintain their peak steady-state rate of performance to maximize their performance during trials. We then use a large dataset of healthy control participants (n = 643, ages 18 to 93) who have performed these tasks to assess aging effects on motor behaviours. We perform linear regressions with a number of motor and cognitive parameters to determine which are significantly impacted by age. We also tested for sex-related effects (male vs. female) on motor behaviours and on aging effects given their occurrence in the sensorimotor and aging literatures.

Methods

Participants

A total of 643 healthy human participants (368 female and 275 male; 64 left-handed, 577 right-handed, and 2 mixed; median age 45) performed the Object-Hit task (Table 1) or the Object-Hit-and-Avoid task (Table 2), with the majority of participants performing both tasks.

Age	n	Median age	Sex		Handedness		
			Female	Male	Left (F/M)	Mixed (F/M)	Right (F/M)
18-29	203	23	120	83	16/10	0/0	104/73
30-39	65	34	32	33	1/2	0/0	31/31
40-49	72	44.5	52	20	4/3	0/0	48/17
50-59	79	56	50	29	3/4	1/0	46/25
60-69	101	64	51	50	6/8	0/0	45/42
70-79	71	74	37	34	2/3	0/0	35/31
80-93	27	84	12	15	0/1	1/0	11/14

Table 1 Participant demographics for OH (n = 618, 354 female and 264 male)

	Age	n	Median age	Sex		Handedness		
				Female	Male	Left (F/M)	Mixed (F/M)	Right (F/M)
1	18-29	163	23	97	66	15/7	0/0	82/59
2	30-39	56	34	31	25	1/1	0/0	30/24
3	40-49	58	45	39	19	4/3	0/0	35/16
4	50-59	65	56	39	26	1/3	1/0	37/23
5	60-69	87	64	43	44	6/8	0/0	37/36
6	70-79	65	74	33	32	2/3	0/0	31/29
7	80-93	19	84	7	12	0/1	1/0	6/11

Table 2 Participant demographics for OHA (n = 513, 289 female and 224 male)

Participants were recruited from Kingston, Ontario and Calgary, Alberta with test procedures⁹ approved by the Research Ethics Boards of Queen's University and Providence Care as well as the¹⁰ Conjoint Health Research Ethics Board at the University of Calgary. All participants gave their¹¹ written and informed consent to have their data collected for research purposes.¹²

Healthy human participants had no significant neurological impairments, were medically stable,¹³ had normal or corrected to normal visual acuity, had no ongoing musculoskeletal injuries of the¹⁴ upper limb, and were able to understand task instructions [28, 29].¹⁵

Apparatus

For both tasks, participants were seated in a bilateral Kinarm exoskeleton lab (Kinarm, Kingston,¹⁸ Ontario; [33]; Fig. 1A), which provides full gravitational support to the upper limbs while allowing¹⁹ movement in the horizontal plane [28].²⁰

Experimental tasks

The OH task tests an individual's ability to generate quick and accurate arm movements throughout²² the workspace. Participants are instructed to use their hands (represented visually as 5 cm green²³ paddles) to hit 300 circular objects (red, 2 cm in diameter) that move towards them in a virtual²⁴ workspace projected in the horizontal plane (Fig. 1B). Objects are dropped from 10 invisible bins²⁵ along the horizontal axis, 30 objects per bin, with each bin dropping an object in random order²⁶ before repeating. Objects are dropped at an increasing rate throughout the trial and with increasing²⁷ speeds [28].²⁸

¹ The OHA task is similar, except that an arbitrary decision rule is introduced based on the red¹
²objects' different shapes (Fig. 1C). Two of the eight shapes are chosen by the task to indicate²
³targets while the remaining shapes are used to indicate distractor objects and these shapes are³
⁴communicated to the participant at the beginning of the trial. Participants were instructed to hit⁴
⁵as many of the 200 targets as possible without hitting the 100 distractor objects [29].⁵

⁶ The exoskeleton robot recorded velocities and positions of the hands and objects during both⁶
⁷tasks with a sampling frequency of 200 Hz. Contact between paddles and objects was simulated⁷
⁸by the exoskeleton robot using a 50 ms force pulse; this feedback was omitted during OHA for⁸
⁹paddle/distractor contacts to provide instantaneous feedback to the participant that the distractor⁹
¹⁰was not a one of the two targets. Once the trial is completed for either task, a number of parameters¹⁰
¹¹are computed to summarize the participant's performance (Table 3). For full details, see the original¹¹
¹²papers by Tyryshkin et al. [28] and Bourke et al. [29].¹²

¹³ Both OH and OHA have been shown to be reliable tests of sensorimotor and cognitive abilities,¹³
¹⁴with no significant learning effect between trials [21]. The lack of learning effects permitted us¹⁴
¹⁵to include multiple trials performed by the same participant, giving us 812 OH trials from 618¹⁵
¹⁶participants and 683 OHA trials from 513 participants.¹⁶

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1				1
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3				3
4	Parameter	Units	Description	4
5	Motor Parameters			5
6	Mean hand speed L/R	cm/s	The participant's mean hand speed for the left/right hand during the trial.	6
7	Mean hand speed bias	$\frac{\text{cm/s}}{\text{cm/s}}$	A value from -1 (all left hand) to 1 (all right hand) which describes the bias in mean hand speed between the hands.	7
8	Movement area L/R	cm ²	Area the participant used with the left/right hand during the trial. Determined by a convex hull that encompasses the complete hand path.	8
9	Movement area bias	cm ² /cm ²	A value from -1 (all left hand) to 1 (all right hand) which describes the bias in movement areas between the hands.	9
10	Hand bias of hits	n/n	A value from -1 (all left hand) to 1 (all right hand) that quantifies which hand is used more often for hitting targets.	10
11	Hand selection overlap	%	The sum of the hand switches for each bin, divided by the number of targets. Expresses how often participants hit targets with both the right and left hands in the same area of the work space.	11
12	Hand transition	cm	Where in the workspace the participant's preference for using one hand over the other switches.	12
13	Miss bias	cm	Where in the workspace the participant's misses are biased.	13
14	Cognitive parameters			14
15	Median error	%	Percentage of the way through the task (based on number of targets, not time) where the participant has recorded half of their misses.	15
16	Distractor proportion	%	Number of distractors hit as a proportion of the total number of objects (targets + distractors) hit. OHA only.	16
17	Object processing rate	Hz	Number of objects (targets + distractors) correctly processed when 80% of the task's objects have been created. OHA only.	17
18	Targets hit	n	The number of targets hit during the trial.	18
19	Steady-state rate	Hz	Number of targets hit per second while the participant is overwhelmed.	19
20	Task Success Parameters			20
21	Task scores	1	A global measure of the subject's performance, with 0 indicating best performance and increasing values indicating worsening performance. Specifically, the root sum of squares distance of the subject's Z-scores and Zeta-scores compared to healthy control subjects.	21
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23				23
24				24
25				25
26				26
27				27
28				28

Table 3 Parameters recorded by the Kinarm and computed for the OH and OHA tasks [3].

¹Data analysis

²Values for the parameters in Table 3 were calculated using Dexterit-E Explorer 3.9 (Kinarm,
³Kingston, ON) and all subsequent analysis was performed using custom scripts in MATLAB (Math-
⁴works Inc., Massachusetts, USA). The sole exception to this was the steady-state rate, which we
⁵observed was a characteristic phenomenon in participants' trials for both OH and OHA. We au-
⁶tomatically calculated the participant's steady-state rate for both tasks by smoothing the target
⁷creation and target hit rates using two iterations of a Kolmogorov-Zurbenko filter with a 5 s sliding
⁸window and then determining the last window in which the median difference between the rates
⁹was less than 0.1 Hz. A participant's steady-state rate is their average target hit rate from this
¹⁰window until the end of the trial (Fig. 2).

¹¹We then performed linear regressions between age and each of the parameters in Table 3 for both
¹²OH and OHA, recording the slope and intercept parameters for these regressions as well as each
¹³parameter's 95% confidence interval. We also recorded the p-value resulting from Student's t-test
¹⁴for the null hypothesis that the slope parameter's value was 0, i.e., that there is no age-related
¹⁵effect.

¹⁷To assess whether there were any differences in parameter values related to participants' sex, we
¹⁸divided participants for both tasks according to their self-reported sex. We performed Student's
¹⁹t-test for each parameter with the null hypothesis that the difference in mean value between males
²⁰and females was 0. We recorded the p-value for this t-test as well as the 95% confidence interval for
²¹the true difference in mean parameter values for male and female participants.

²²Finally, we tested the age-related declines of parameters with meaningful effect sizes for sex-related
²³effects. We again divided participants for both tasks according to their self-reported sex. We then
²⁴performed a Z-test between the regression slopes, b , for each parameter, calculating the Z-statistic
²⁵computed according to (1), with the null hypothesis for each test being that the regression slopes
²⁶for males and females were identical [34]. We recorded the two-tailed p-value from each test.

$$Z = \frac{b_{male} - b_{female}}{\sqrt{SE(b_{male})^2 + SE(b_{female})^2}} \quad (1)$$

¹ To account for the number of comparisons that we performed, we used the Bonferroni cor-¹
²rection [35]. Since this study includes 68 comparisons, the significance level 0.05 is corrected to²
³ 7.4×10^{-4} .³

⁴

⁵**Results**⁵

⁶Task validity⁶

⁷ There are two aspects of OH and OHA that must be verified in order to confirm that they are⁷
⁸ suitable for evaluating healthy human participants' rapid motor behaviours.⁸

⁹ First, we want to verify that these tasks are sufficiently challenging that healthy participants⁹
¹⁰ must achieve their peak performance in order to do well. The ranges of targets hit in both tasks¹⁰
¹¹ are within the total number of targets produced and the distributions are roughly normal, with the¹¹
¹² Kolmogorov-Smirnov test failing to reject the null hypothesis for either task [36]. The width of the¹²
¹³ distributions, their median values, and the lack of either ceiling or floor effects all indicate that the¹³
¹⁴ tasks are capable of capturing a wide range of performance levels in healthy participants (Fig. 3).¹⁴

¹⁵ Second, we want to verify that participants adhere to task instructions. This is especially necessary¹⁵
¹⁶ for OHA, where two potentially conflicting instructions are given. Scatter-plotting the number of¹⁶
¹⁷ targets hit against the number of distractors avoided shows that most participants were successful in¹⁷
¹⁸ avoiding distractors. There is a positive correlation between hitting targets and avoiding distractors,¹⁸
¹⁹ the linear regression slope is 0.16, telling us that there is no trade-off between the two objectives¹⁹
²⁰ and that skilled participants were better at both hitting targets and avoiding distractors (Fig. 4).²⁰
²¹ Participants' relative success at avoiding distractors, seen by the intercept term of 0.64, suggests²¹
²² that this instruction was prioritized during OHA. Taken together, these findings tell us that we²²
²³ can measure success in OHA by the number of targets hit because we do not have to account for²³
²⁴ variable amounts of effort made by participants to hit targets or avoid distractors.²⁴

²⁵

²⁶Steady-state rates in rapid motor behaviour tasks²⁶

²⁷ As illustrated in Fig. 2, we observed that participants became overwhelmed by the number of targets²⁷
²⁸ in the environment for both tasks. When this occurred, participants hit targets at a steady-state²⁸

rate regardless of how many additional targets the task produced. This confirms our belief that participants are required to produce peak performance in order to achieve their best results.

We defined the overwhelmed phase as beginning in the last 5 s window where the median difference between target creation and target hit rates was less than 0.1 Hz; the early phase of the task occurs before this when the participant keeps up with the target creation rate. We observed that participants adopted two distinct strategies for these two phases, illustrated by their “per-bin” target accuracies (Fig. 5). In the early phase of the task, participants were able to hit more than 95% of targets, regardless of the targets’ horizontal bin. The limit on the target hit rate during this phase was the task’s target creation rate.

In the overwhelmed phase of the task, a participant’s target hit rate was limited by their own abilities. Trade-offs between speed, accuracy, and effort were required to maximize and maintain the steady-state rate. Not only did participants hit fewer targets during the overwhelmed phase, but they also shifted to a strategy of hitting targets in the central bins while allowing more than 50% of targets in the outermost bins, which required the most time and effort, to pass through the workspace unhit.

The instruction to participants across both tasks is to hit as many targets as possible, which makes it the natural way to evaluate how well a participant performed. Figure 6 shows that steady-state rates and number of targets hit correlate very well for both OH and OHA.

19

19

Age-effects in OH and OHA

Tables 4 and 5 report the estimated slope parameters for linear regressions between age and each of the parameters of interest for the two tasks.

We observe that motor-related parameters, such as mean hand speeds or movement areas, show no decrease with age for either task. The only p-values that are significant at the corrected level indicate an increase in mean hand speed for both the left and right hands in OH and a decrease in movement area with the left hand in OHA. These effect sizes are incredibly small: every decade of age results in the mean hand speed for both hands increasing by 0.005 cm/s.

28

$$0.0005 \frac{\text{cm}}{\text{yr}} \times 10 \text{ yr} = 0.005 \text{ cm/s}$$

28

Parameter	Slope	95% CI	p
Mean hand speed left	0.0005	(0.0003, 0.0007)	2.289×10^{-6}
Mean hand speed right	0.0005	(0.0003, 0.0007)	4.853×10^{-6}
Mean hand speed bias	-1.172×10^{-5}	(-0.0002, 0.0002)	0.9215
Movement area left	1.173×10^{-6}	(-9.401×10^{-5} , 9.636×10^{-5})	0.9807
Movement area right	3.731×10^{-5}	(-6.349×10^{-5} , 0.0001)	0.4677
Movement area bias	0.0002	(-9.620×10^{-5} , 0.0005)	0.1994
Hand bias of hits	0.0003	(7.599×10^{-5} , 0.0006)	0.0106
Hand selection overlap	-8.004×10^{-5}	(-0.0002, 5.239×10^{-5})	0.2358
Hand transition	-8.666×10^{-5}	(-0.0002, 4.433×10^{-6})	0.0622
Miss bias	0.0002	(5.478×10^{-6} , 0.0003)	0.0427
Median error	-0.1058	(-0.1228, -0.0888)	1.279×10^{-31}
Targets hit	-0.7333	(-0.8212, -0.6455)	2.550×10^{-52}
Steady-state rate	-0.0099	(-0.0111, -0.0087)	4.150×10^{-52}
Task score	-0.0020	(-0.0041, 1.467×10^{-4})	0.0680

Table 4 Estimated values and 95% confidence intervals of the slope parameter for linear regressions between age and the parameters listed in Table 3 for OH. Also included are p-values for the null hypothesis that a regression's slope parameter is equal to 0.

Over a 60-year span of adulthood, this would result in a total increase of only 0.03 cm/s .

$$0.0005 \frac{\text{cm/s}}{\text{yr}} \times 60 \text{ yr} = 0.03 \text{ cm/s}$$

Conversely, cognitive parameters generally decline with age with meaningful effect sizes over the course of an average human lifespan. In OH, every decade of life moves participants' median error forward by an average of 3 objects in the task.

$$-0.1058\%/\text{yr} \times 300 \text{ obj} \times 10 \text{ yr} = 3.17 \text{ obj}$$

Every decade of life also reduces on average a participant's OH steady-state rate by 0.1 Hz—6 targets per minute—and reduces their number of targets hit by 7. Over the course of 60 years of adulthood, this results in steady-state rates that are 0.6 Hz lower and 42 fewer targets hit over a single trial, which represents 14% of all available targets.

Participant performance in OHA saw similar declines in cognitive parameters, with every decade of life reducing steady-state rates by 0.077 Hz on average and the number of targets hit by 6.

Parameter	Slope	95% CI	p
Mean hand speed left	-0.0002	$(-0.0004, -2.800 \times 10^{-5})$	0.0222
Mean hand speed right	-0.0003	$(-0.0005, -0.0001)$	0.0015
Mean hand speed bias	-0.0002	$(-0.0005, 0.0001)$	0.2358
Movement area left	-0.0002	$(-0.0003, -0.0001)$	3.563×10^{-5}
Movement area right	-0.0002	$(-0.0003, -8.192 \times 10^{-5})$	0.0003
Movement area bias	0.0001	$(-0.0002, 0.0005)$	0.4462
Hand bias of hits	-0.0001	$(-0.0005, 0.0002)$	0.3678
Hand selection overlap	-0.0003	$(-0.0004, -0.0001)$	0.0003
Hand transition	-6.746×10^{-5}	$(-0.0002, 5.309 \times 10^{-5})$	0.2723
Miss bias	9.184×10^{-5}	$(-8.422 \times 10^{-5}, 0.0003)$	0.3061
Median error	-0.1360	$(-0.1558, -0.1163)$	4.509×10^{-37}
Distractor proportion	0.1307	$(0.1112, 0.1502)$	1.960×10^{-35}
Object processing rate	-0.0100	$(-0.0111, -0.0089)$	5.772×10^{-62}
Targets hit	-0.6120	$(-0.6739, -0.5501)$	3.762×10^{-67}
Steady-state rate	-0.0077	$(-0.0085, -0.0069)$	1.226×10^{-62}
Task score	-0.0014	$(-0.0038, 0.0010)$	0.2500

Table 5 Estimated values and 95% confidence intervals of the slope parameter for linear regressions between age and the parameters listed in Table 3 for OHA. Also included are p-values for the null hypothesis that a regression's slope parameter is equal to 0.

Participants also became increasing worse at avoiding distractor objects, with distractor proportions increasing on average by 7.8 percentage points from age 20 to age 80.

$$0.1307\%/_{\text{yr}} \times 60 \text{ yr} = 7.84\%$$

Scatter plots for selected parameters with significant aging effects are shown in Fig. 7.

Sex-effects in OH and OHA

Table 6 reports the estimated value and 95% confidence intervals for the difference in mean parameter values between male and female participants.

Two motor parameters, both movement areas, show a sex-based effect in OH but the effect sizes for the motor parameters are incredibly small: male participants used an additional 0.1 cm^2 with both hands compared to an overall workspace size of $5,200 \text{ cm}^2$. On the whole, then, there are no practical differences between motor parameters for male and female participants.

Parameter	OH		OHA	
	p	95% CI	p	95% CI
Mean hand speed left	0.01528	(0.0020,0.0190)	0.0041	(0.0032,0.0169)
Mean hand speed right	0.0367	(0.0006, 0.0184)	0.5264	(-0.0049,0.0095)
Mean hand speed bias	0.3546	(-0.01460, 0.0052)	0.0015	(-0.0343,-0.0082)
Movement area left	1.007×10^{-11}	(0.0101,0.0180)	0.0002	(0.0036,0.0116)
Movement area right	1.2181×10^{-8}	(0.0083,0.0169)	0.2091	(-0.0015,0.0069)
Movement area bias	0.1553	(-0.0205,0.0033)	0.0007	(-0.0424,-0.0114)
Hand bias of hits	0.1305	(-0.0187,0.0024)	0.0202	(-0.0281,-0.0024)
Hand selection overlap	0.1500	(-0.0015,0.0097)	0.0189	(0.0013,0.0147)
Hand transition	0.7218	(-0.0032,0.0047)	0.1063	(-0.0009,0.0092)
Miss bias	0.8718	(-0.0064,0.0075)	0.7090	(-0.0059, 0.0087)
Median error	1.0424×10^{-6}	(1.169,2.717)	0.5847	(-1.195,0.6743)
Distractor proportion	—	—	0.6504	(-0.6866,1.099)
Object processing rate	—	—	0.0646	(-0.0031,0.1043)
Targets hit	4.144×10^{-11}	(9.9753, 18.2396)	0.0548	(-0.0655, 6.3569)
Steady-state rate	1.110×10^{-10}	(0.1326,0.2461)	0.0516	(-0.0003,0.0828)
Task score	0.6760	(-0.0722, 0.1112)	0.5732	(-0.0711, 0.1284)

Table 6 Population differences and statistical test results for sex effects in both OH and OHA.

Three cognitive parameters show a sex-based effect in OH: median error, number of targets hit, and steady-state rate. All three parameters indicate that male participants hit between 10 and 18 more targets than female participants during an OH trial. This difference is 3%-6% of all available targets and 5%-9% of the range of targets hit in OH (Fig. 3A). These differences disappear in OHA, however, and we see no sex-based effects on performance in the OHA task for either motor or cognitive parameters.

Age-related declines for parameters with significant effects and meaningful effect sizes were tested for any sex-based effects by comparing regression slopes between male and female participants. Aging-related declines were similar for male and female participants (Table 7).

Discussion

It is well understood that the human sensorimotor system diminishes with age [6, 7, 8, 9, 15, 10, 11, 12, 13, 14, 16, 17]. These diminishing abilities are the result of impairments in both the muscular and nervous system, and there is evidence that impairments in the brain and nervous system can lead directly to muscular impairments such as muscle weakness [37]. We systematically studied the

Parameter	OH	OHA
Median error	0.9503	0.8046
Distractor proportion	—	0.7078
Object processing rate	—	0.6902
Targets hit	0.6908	0.2879
Steady-state rate	0.2958	0.3121

Table 7 Z-test p-values for the null hypothesis that male and female participants had the same regression slopes for age-parameter regressions.

effects of age on rapid motor skills with two interactive tasks: OH and OHA. Our results show that an individual’s age-related decline in performance for both tasks is best seen in cognitive parameters, not motor parameters, and that there is no sex-related effect for this decline. This suggests that age-related motor deficits may result from diminished neural abilities, such as planning or decision-making, as much as any reduction in strength or coordination. Three cognitive parameters showed significant sex effects in OH, but no parameter showed a significant sex effect in OHA.

Both OH and OHA push participants to perform at the peak of their abilities. Although younger participants outperformed older participants in both tasks, this did not result from higher mean hand speeds, larger movement areas, or less bias in hand selection. In fact, the only motor parameters that showed any significant change with age was the mean speed of each hand and this increased with age. We dismissed this change due to the small effect size, but note a possible explanations. As a mean value, the mean hand speed parameters do not capture peak motor activity. It is possible that younger participants were able to reach higher peak speeds than older participants when necessary. It is also possible that high mean hand speeds in older participants is a reflection that they become overwhelmed earlier in the task and therefore spend longer in the overwhelmed phase marked by vigorous movement.

Instead younger participants derived their advantage in performance from higher steady-state rates: when it came to peak performance, younger participants could sustain a higher rate of hitting targets. These higher steady-state rates are reflective of an ability to perform the OH and OHA tasks at more challenging levels. This may be evidence that older adults’ are able to compensate for cognitive declines up to a certain point. This would be in line with the compensation-related

¹utilization of neural circuits hypothesis, which posits that the aging brain's inefficient processing¹
²requires it to recruit more neural resources than a younger brain in order to achieve the same²
³output [38, 39]. It would also be consistent with the scaffolding theory of aging and cognition,³
⁴which integrates the activation of neural resources in response to aging and challenge into one⁴
⁵mechanism [40].⁵

⁶Of course, these are general, population-level results. Some older participants did much better⁶
⁷than their age cohort, hitting as many targets as and maintaining steady-state rates similar to⁷
⁸participants who were decades younger. It is unclear whether or not these individuals began at⁸
⁹superlative levels of performance before declining with age, or if they are "super-agers" who have⁹
¹⁰maintained their fitness well into their old age [41]. Super-agers' neuroanatomy is well-preserved and¹⁰
¹¹shares similarities with the neuroanatomy of younger adults [42]. This supports superior cognitive¹¹
¹²skills, such as attention and memory encoding, and higher processing speeds compared with other¹²
¹³older adults [42, 43]. It is possible that this preservation of cognitive abilities has allowed these¹³
¹⁴individuals to minimize their performance drop over the decades, although a more detailed analysis¹⁴
¹⁵of this issue is beyond the scope of the present study.¹⁵

¹⁶We noted sex-based effects on cognitive parameters during OH, including on the number of targets¹⁶
¹⁷hit, but not during OHA. This is not due to any additional speed or range of movement by male¹⁷
¹⁸participants, however, since we found no practical differences in motor parameters for either task¹⁸
¹⁹(Table 6). Since the main distinction between the two tasks is OHA's introduction of distractor¹⁹
²⁰objects, we investigated whether participants responded differently based on their sex, but found²⁰
²¹no evidence to support this idea. A possible explanation is that male participants have trained their²¹
²²sensorimotor skills through their disproportionate representation in both sports, [44, 45, 46], and²²
²³esports [47]. The arbitrary decision rule introduced for OHA may have then been sufficiently unfa-²³
²⁴miliar as to negate this training, an effect that has been reported in high-performance athletes [48].²⁴
²⁵This is a speculative explanation concerning a population-level result, however, and likely does not²⁵
²⁶capture individual variance. Further study is required to establish the validity of this explanation.²⁶

²⁷We believe that OH and OHA are both useful for studying interactive motor behaviour. In both²⁷
²⁸tasks, participants must decide about future actions while executing current actions, all while²⁸

potential targets are continuously created independent of participant action. This “decide-while-¹acting” paradigm, [31], aligns well with the everyday behaviours that we are most concerned about² with aging such as driving or walking along crowded streets. ³

⁴ The freedom to act in an interactive environment also opens the door to ecological interpretations⁵ of our results [49]. Participants performing OH and OHA make embodied choices, where action⁶ performance is an integral part of decision-making [50, 51]. In embodied cognition, sensorimotor⁷ decision problems consist of perceiving affordances in the environment [52] and then selecting from⁸ among potential actions through competition [53, 54]. Embodied cognition implies that the senso⁹rimotor system uses an internal model of itself, allowing it to represent and reason about its own¹⁰ abilities and limitations [55]. This is theoretically sound as an example of the Internal Model Prin¹¹ciple: successful control of a system vulnerable to disturbances requires the controller to incorporate¹² a model of the disturbance and of the system itself [56, 57]. Practically, there is evidence that older¹³ adults suffer from a degraded internal model—they are less embodied—and that they compensate for¹⁴ this degraded model by relying on visual feedback in sensorimotor tasks [12]. Thus the age-related¹⁵ process deficits we observe in this study may be the result of older adults being more reliant on¹⁶ external, noisy signals than younger adults. ¹⁷

¹⁸ A clear finding in our study is the importance of cognitive parameters, which is in line with ¹⁸
¹⁹ many views in the sensorimotor literature including: that interactive behavior is produced by the ¹⁹
²⁰ simultaneous processes of specifying and selecting motor actions [49]; that skilled motor performance ²⁰
²¹ requires multiple interacting processes to be learned [58]; and that motor actions are the result of ²¹
²² hierarchical goal, state, and action processes [59]. Specifically, we highlight the steady-state rate ²²
²³ parameter that we uncovered as an indicator of peak performance in both OH and OHA. Reaching ²³
²⁴ a steady-state rate of hitting targets is associated in both tasks with a clear strategic shift to ²⁴
²⁵ hitting targets in the central part of the workspace, which may be the result of failing to perceive ²⁵
²⁶ the most lateral targets or deciding to minimize movement costs. Although this question must be ²⁶
²⁷ left to future study, we believe that measures like the steady-state rate serve as strong support for ²⁷
²⁸ ongoing, interactive tasks. Unlike reaction time tasks where participants decide and then act, tasks ²⁸

set in interactive environments allow steady-state rates to be used as an ongoing reaction time when measuring participants performance of continuing, interactive behaviours.

As a limitation, our study used only two tasks to assess individuals' rapid motor behaviours and because OHA was conceived of as an extension to OH, these tasks were related. Our results are therefore specific to this kind of target-hitting task and may not generalize across other motor behaviours. Future studies should seek to replicate these findings using other interactive tasks in order to ascertain whether neural processes are universally implicated in age-related motor decline or whether there are distinct classes of motor behaviours. Additionally, our study was cross-sectional in nature and not longitudinal. As we covered in our discussion concerning "super-agers," it is possible that some of our findings reflect idiosyncratic characteristics of our age groups, though the study's large cohort size should allay these concerns. Regardless, there is evidence that individuals age differently and longitudinal studies may reveal details about age-related declines in rapid motor behaviours that have escaped our notice.

Conclusions

This study has established that age-related declines in motor abilities can be studied using the OH and OHA tasks specifically and rapid, interactive behaviour tasks more broadly. Our results suggest that age-related declines in these behaviours have more to do with cognitive processes than with more basic motor abilities. This is in line with evidence that normal aging is accompanied by reduced cognitive processing abilities and may be connected to older adults' less reliable internal models. We found very limited evidence that sex affected motor behaviours in the two tasks we considered and found no evidence that sex affected the age-related declines that we reported in motor abilities. This work will help the establishment of new neuropsychological tests and equipment for assessing individuals' motor skills throughout the aging process.

Abbreviations

OH: Object-Hit; OHA: Object-Hit-and-Avoid

Ethics declaration

All test procedures were approved by the Research Ethics Boards of Queen's University, Providence Care, and the University of Calgary. All participants gave their written and informed consent to have their data collected for research purposes.

1 Availability of data and materials

2 The datasets analysed during the current study are available from Stephen H. Scott (steve.scott@queensu.ca) on reasonable request.
3 All custom MATLAB code used in the analysis of this data is available on Github at DOI 10.5281/zenodo.6110739.

4 Competing interests

4 SHS is the co-founder and Chief Scientific Officer of Kinarm (formerly BKIN Technologies), the company that commercializes the robotic
5 technology used in this study. RHM, KR, and SPD have no competing interest to disclose.

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8 and Applied Science (RHM).

9 Author's contributions

9 SPD and SHS coordinated the collection of data. RHM analysed the data and drafted the manuscript. SHS provided the concept. KR and
10 SHS both provided direction. All authors contributed to editing and both read and approved the final manuscript prior to submission.

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Figures

Figure 2 The steady-state rate. Smoothed target creation (black) and target hit (blue) rates are shown for an illustrative participant performing an OH trial. At a certain point in the trial, the participant becomes overwhelmed by the targets being created and reaches a steady-state rate of hitting targets (red).

Figure 3 Targets hit. Histograms showing the number of targets hit by participants across all trials for (A) OH and (B) OHA. Note that there are 300 targets in OH but only 200 targets for OHA.

Figure 4 No trade-off between targets and distractors. Scatter plots showing the proportion of targets hit versus the proportion of distractors avoided for OHA. The linear regression line is shown in solid red along with the 95% confidence interval in dashed red. The solid black line indicates equal trade-off between the two objectives, with perfect performance in the top right corner. The dashed black line indicates hitting objects indiscriminately, with no distinction between targets and distractors.

Figure 5 Participants have different per-bin accuracies during different phases of the trial. Mean percentage of targets hit by horizontal bin across all trials for (A) OH and (B) OHA. The standard error of the mean is shown as bars for each point, but largely overlaps with the mean itself. Targets are split according to whether they were created during the participant’s individual early (blue) or overwhelmed (red) phase.

Figure 6 Hits and stead-state rates correlate. Participants’ number of targets hit and steady-state rate are scatter-plotted for (A) OH and (B) OHA. Linear regression lines are shown in red.

Figure 7 Age-related declines in OH and OHA. Scatter plots between participant age and parameters showing significant aging effects for (A) OH and (B) OHA. Linear regressions are shown in solid red and the regression's 95% confidence intervals are shown in dashed red.

¹ Additional Files	1
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