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ORIGINAL RESEARCH ARTICLE

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Effect of sub-maximal physical fatigue on auditory and visual reaction time in healthy adults: repeated measures design

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Abstract

Background Auditory reaction time (ART) and visual reaction time (VRT) are critical for patients with stroke, especially during balance training. According to the research, most patients with stroke are fatigued at sub-maximal levels during their stroke rehabilitation. Sub-maximal physical fatigue may affect ART and VRT and impede stroke rehabilitation. Hence, it is important to study the effect of submaximal physical fatigue on ART and VRT. A pilot study on healthy adults paves the way for further research on stroke rehabilitation. The purpose of this research is to find out if sub-maximal physical fatigue affects ART and VRT in healthy adults. In addition, this study also determines if ART and VRT recover to baseline after 15 min of rest post-fatigue session. Furthermore, the goal is to determine whether sub-maximal physical fatigue has a greater effect on ART or VRT.

Methods A repeated measures within-subject design was used in the study. Eighteen healthy participants (median age 24 years) completed two sessions of a sub-maximal fatigue protocol on a cycle ergometer until they reached a rating of perceived exertion (RPE) of 15 on a scale of 6–20. Two different fatigue sessions were conducted (one to study the effects of fatigue on ART and the other for VRT). ART or VRT was measured on computer software before (PRE), immediately after (POST-0), and 15 min after (POST-15) the sub-maximal physical fatigue protocol.

Results The value of median ART increased significantly from PRE to POST-0 ($P=0.002$) and it decreased significantly at POST-15 ($P=0.010$). Similarly, the value of mean VRT increased from PRE to POST-0 ($P=0.001$) before decreasing significantly at POST-15 ($P=0.001$). There was no significant difference between the effects of submaximal fatigue on ART and VRT ($P=0.156$).

Conclusion Due to submaximal physical fatigue, ART and VRT were slower, but they returned to baseline after 15 min of rest. Submaximal physical fatigue had an equal impact on ART and VRT. As balance training requires quicker ART and VRT for optimal outcomes, it may be better if the physiotherapists consider a 15-min rest period between the exercise and balance training in patients with stroke.

Keywords Physical fatigue, Sub-maximal physical fatigue, Cycle ergometer, Auditory reaction time, Visual reaction time, Rehabilitation

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Background

Simple reaction time (RT) is the length of time that passes between the presentation of an unexpected stimulus and the start of the response to that stimulus [1]. It is an indirect measure of the central nervous system's ability to receive, process, and respond to unexpected incoming stimuli [1]. Auditory reaction time (ART) and visual reaction time (VRT) are the most important because they are used in everyday life as well as in stroke rehabilitation.

The importance of ART and VRT for stroke patients is well-documented [2, 3]. They are very crucial for stroke patients because if RT is slower, it can affect their rehabilitation as well as their quality of life. Slower reactions make it difficult to recover from perturbations and restore balance leading to falls [4]. Hence, any factor that can affect RT must be analyzed. Physical fatigue is one of the factors that can affect RT and increase the risk of falls in stroke rehabilitation [5].

Physical fatigue is an exercise-induced decrease in muscle force output [6]. It appears gradually after the exercise starts and includes feelings about tasks being more difficult or requiring more effort than expected [7]. Due to poor aerobic fitness, physical fatigue is more common in stroke patients, especially during exercises that involve the entire body, such as treadmill walking and cycling. Such patients experience physical fatigue of sub-maximal intensity during stroke outpatient rehabilitation [8, 9]. Most stroke patients rate their fatigue intensity as 14–16 on a rating of perceived exertion (RPE) scale [10, 11]. This scale is commonly used to assess fatigue.

Physical fatigue may slow the RT via central and/or peripheral mechanisms [5]. Fatigue originating proximal to the neuromuscular junction is central fatigue while distal to it is peripheral fatigue. Doyle-Baker et al. 2018 stated that peripheral fatigue reduces the actin-myosin interaction, excitation–contraction coupling, and sarcolemma action potential transmission which are necessary for nerve impulses to reach the muscle faster allowing for faster responses. Because peripheral fatigue causes nerve impulses to reach slower to the muscles, this leads to slower reactions. Conversely, central fatigue causes motor unit deactivation, which eventually slows the motor cortex's signal for faster muscle contractions, slowing RT [6].

Summary of existing literature on the effects of fatigue on RT

The effects of physical fatigue on VRT were studied by Ozdemir et al. in 18 athletes in 2010. The VRT was slower post-fatigue protocol on the cycle ergometer [12]. On the other hand, Pavelka et al. 2020 fatigued 18 male athletes on an arm ergometer and found VRT to be slower post-fatigue [13]. However, both these studies [12, 13] considered fatigue of maximal intensity. In addition, other limitations include gender bias as they did not consider the equal number of male and female participants. Pavelka et al. study did not mention if they asked participants about the consumption of caffeine, smoking, or alcohol consumption [13]. Caffeine ingestion lowers RPE, increases HR, and affects RT [14].

Coco et al. in 2020 studied the effects of sub-maximal physical fatigue on a cycle ergometer at two fatigue intensities (60 and 80% of VO_{2max}) on VRT in 20 males. VRT was affected only after the exercise at 80% of VO_{2max}. RPE and HR are more commonly used compared to VO_{2max} to measure exercise intensity in stroke rehabilitation [15]. One more study by Coco et al. in 2020 fatigued 15 young and 15 old participants on a cycle ergometer until maximal exhaustion. The VRT was slower post-fatigue which returned to baseline after 15 min post-termination of the exercise session [16]. The strengths of both studies [15, 16] are the inclusion of warm-up before cycling, and following the ethical guidelines. The limitations of both studies include no sample size calculation causing selection and sampling bias. In addition, both studies assessed other cognitive tasks with VRT and there was no mention of sequence of assessment. Hence, fatigue recovery is probable at the time of VRT measurement affecting the study results.

Morrison et al. in 2016 studied the effects of walking-induced sub-maximal fatigue on VRT in 75 healthy individuals of 30–79 years. The participants were asked to walk on the treadmill at their faster speed. Three sets of 5 min with 5 min of rest between the sets were conducted. The VRT was affected in older groups (60–79 years) but not in younger groups [17]. The results might be affected because of the rest period during the fatigue protocol. Carroll et al. in 2017 stated that partial recovery from fatigue starts immediately after the termination of exercise [18].

The effect of physical fatigue on RT varies with exercise intensity [12]. Sub-maximal physical fatigue is common in stroke patients, but no methodologically good studies have been conducted to investigate its effects on ART and VRT. Furthermore, while physical fatigue can be recovered over time [19], its effects on RT may or may not persist. There has been no research into how ART and VRT change during submaximal fatigue recovery. Furthermore, no research has been conducted to compare the effects of submaximal fatigue between ART and VRT. Given the paucity of research in this area, a trial on a healthy population should be carried out to see if submaximal physical fatigue affects ART and VRT.

Filling this gap in the literature is critical. ART and VRT are crucial during stroke balance rehabilitation. Submaximal physical fatigue can make it difficult for stroke patients to react quickly during balance rehabilitation. Understanding the effects of submaximal physical fatigue on ART and VRT will help physical therapists determine how long to wait between exercises and balance training during stroke rehabilitation. This could help in creating a more tailored rehabilitation plan to improve therapy outcomes from balance training and reduce the risk of falls during stroke rehabilitation. Researchers and practitioners can choose which stimulus (visual or auditory) to use when the patients are fatigued during stroke rehabilitation by understanding which RT (ART or VRT) is less prone to fatigue and which is more prone to fatigue [20]. This will eventually improve stroke survivors' physical therapy.

This study aims to determine whether ART and VRT are affected by sub-maximal physical fatigue and 15 min of recovery in healthy adults. In addition, the purpose of this study is to determine whether the effects of submaximal physical fatigue are more on ART or VRT in healthy adults.

Methods

Study design

Because there was only one group of participants, the study used a within-subject experimental design. A one-way repeated measures design (Fig. 1) was used. The dependent variables were RT (ART and VRT).

Sample size

Based on sample size calculations with G power software, a sample size of 19 was required to achieve 80% power with a level of significance of 0.05 and a medium effect size of 0.25. The medium effect size was decided based on researcher's judgement because there is a lack of previous similar research data [21]. However, recruiting only 18 participants was feasible given the study's time frame.

Participants

Nine males and nine females were selected to minimize the gender effect, improve sample homogeneity, and reduce Type I errors [21]. Because obtaining a true random sample is difficult in clinical settings [21], non-probability sampling (convenience sampling) was used. The current study's recruitment strategy included distributing invitation posters and participation information sheets via the Cardiff University intranet portal and student university emails with the help of the program manager and director. The lead researcher was approached by interested students who met the eligibility criteria listed in Table 1.

Location of the data collection and access arrangements

The study was carried out in Cardiff University's Research Laboratory in the Ty Dewisant building on the Heath campus in December 2022. To avoid interference from outside distractions, the study took place in a quiet environment. Temperature and light, which can affect RT [25] were kept constant.

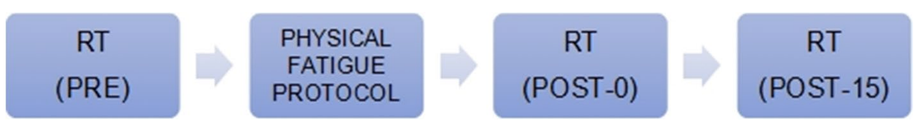

Fig. 1 Study design for ART and VRT

Table 1 Inclusion and exclusion criteria of the participants:

	Reasons
Inclusion criteria	
Cardiff University healthy students (both males and females) with the age of 18 years and above	To improve the generalizability of results
Ability to perform cycling	The sub-maximal physical fatigue was induced on a cycle ergometer in this study
Exclusion criteria	
History of a visual (e.g., color blindness) or hearing disorder [22, 23]	ART and VRT measurements require adequate vision and hearing sense
Participants with the habit of smoking or alcoholism [22, 23]	RT and exercise performance are affected by smoking and alcohol which may affect the results
Participants with cardiovascular or respiratory disease [23]	The exercise performance on the cycle ergometer may be affected if they have any cardiovascular problems
Participants on any medication that can affect cognitive performance [22, 23]	Participants whose cognitive abilities are affected by any medications may already have affected RT scores
History of lasting injury or illness in the lower limbs or spine and lower limb surgery [24]	Such participants may not be able to cycle effectively
Excessive obesity (> 30 BMI) [24]	RT varies with obese individuals
Lower limb pain during the execution of the cycling [24]	Cycling may be affected

Risk assessment

The American College of Sports Medicine (ACSM) recommendations for exercise testing [26] were followed in this study. The study only included participants who answered 'no' to all questions on the Physical Activity Readiness Questionnaire (PAR-Q). During the fatigue protocol on the cycle ergometer, the researcher stood near the participants to monitor HR and RPE and to prevent oxygen saturation from falling below 85%. To avoid soft tissue injury, all participants warmed up before cycling. If any participants felt uncomfortable during the test, they were given the option to stop and rest. For VRT and ART, RT was assessed with a laptop at eye level with appropriate brightness and sound. The risk score was 4, according to Cardiff University's Risk Assessment Tool, which suggests that no further action was required.

Confidentiality of subjects and data protection and storage

A unique code known only to the researcher was used instead of the participant's names on the data collection sheet and PAR-Q forms. All research data was saved in a password-protected file under Cardiff University regulations and the Data Protection Act (1998). Consent forms and PAR-Q forms were kept in a locked cabinet. All collected data will be destroyed 5 years after the study is completed.

Pilot study

To standardize the data collection protocol, a pilot study was conducted on two participants before the main study.

Main study

Venue preparation

The study was conducted in a quiet corner of the research laboratory. Tables and chairs were set up to measure RT on the laptop and baseline parameters before and after cycling. Wattbike was set up similar to the Guzmán and López-Garca study in 2016, with participants facing the wall to reduce environmental distractions [27]. Folding screens were used to create a changing space for participants. All equipment was sanitized with alcohol wipes after the data collection of each participant.

Instructions to the participants before the study

Participants were informed to avoid smoking, caffeine and alcohol consumption, and any vigorous activity 24 h before the study as all these factors affect RT and exercise performance [14, 28]. They were also informed to arrive at the study location hydrated [29]. However, drinking water facilities were made at the study location.

Data collection day

The consent forms were signed and the PAR-Q was filled by the participants. In addition, other information about the participants was collected such as their age, gender, hand dominance, hours of sleep one night before data collection, consumption of caffeine, alcohol, smoking, or if they did any vigorous physical activity 24 h before the study. Then, the height and weight were measured with portable height measuring equipment (Seca Leicester Portable Height Measure, Germany) and a digital weighing scale (Seca Model 862 Flat Scale, Germany), respectively.

Study protocol

The effect of sub-maximal physical fatigue on ART and VRT was studied in two different sessions. There was a three-hour washout period between the two sessions. This washout period was decided based on previous studies [30–32]. The washout period ensures that each session has a consistent baseline, eliminating any long-term fatigue effects from the first session [21].

Both sessions included RT measurements before (PRE) and after (POST-0 and POST-15) the sub-maximal physical fatigue protocol. The only difference was that ART was measured in the first session, while VRT was measured in the second. In addition, HR, RPE, and oxygen saturation were also recorded at these time intervals.

First session (Morning 9 am to 1 pm):

ART(PRE) ---->Submaximal fatigue protocol---->ART (POST0) ---->ART (POST 15).

Second session (Afternoon 1 pm to 5 pm):

VRT(PRE)---->Submaximal fatigue protocol---->VRT (POST0) ---->VRT (POST15).

Outcome measures

The outcome measures in this study were ART and VRT, which were evaluated on a laptop using the "cognitivefun.net program" software (build a2ef7f1). This software has been used in previous studies [33–35]. The software generated a random auditory or visual stimulus, to which the participant had to react quickly by pressing the spacebar with their index finger. The software calculated the time it took from stimulus generation to pressing the spacebar key in milliseconds (ms). Similar to Ozdemir et al. study [12], RT less than 160 ms and greater than 1000 ms was not documented by the researcher because they are anticipation errors and omission errors respectively.

ART

The researcher demonstrated the ART task first, which participants practiced to ensure they understood (Fig. 2). Practice was limited to three times to avoid practice and learning effects. They wore headphones and were blindfolded to avoid visual cues interfering with the auditory stimulus, as done in Verma et al. study [36]. The participant had to press the spacebar key in response to a 'beep' sound (Fig. 3). Five readings were taken.

VRT

VRT demonstration and practice were given. Participants wore headphones during the VRT, as done in the Verma et al. study [36], to reduce environmental noise from interfering with the visual stimulus. They were not blindfolded because they needed to see the laptop screen. They had to react quickly by pressing the spacebar key when the small red dot turned into a large green dot (Fig. 3). The visual stimulus was in the center of the field of vision. Five readings were taken.

Following the evaluation of ART or VRT (PRE), baseline vital parameters such as HR, RPE, and oxygen saturation were obtained. HR was measured using a Polar HR monitor (Polar, Inc., T31 coded, Lake Success, NY, USA), with a Polar FT2 watch (Polar, China) worn on the right hand's wrist and its strap placed on the chest at the xiphoid process. The oxygen saturation was measured on the right index finger with a pulse oximeter (ChoiceMmed, MD300C19, serial number 221909103923).

Sub-maximal physical fatigue protocol

Following the PRE-RT and baseline vital parameters measurements, the participants were fatigued sub-maximally on Wattbike (Wattbike Ltd., Nottingham, UK), an air and mechanically braked cycle ergometer (Fig. 4). It is reliable and valid equipment that has been used in numerous studies to induce physical fatigue [37–39].

The participants had to pedal between 50 and 60 rpm on a watt bike while the resistance was increased incrementally to elicit fatigue. The display on the cycle provided visual feedback, which aided in maintaining the cycling rate. To increase pedal resistance, the watt bike offered both air and magnetic resistance. Initially, air resistance was used, followed by magnetic resistance if necessary.

The fatigue induction methodology was similar to that used in the Ashnagar et al. study [1]. However, the termination criteria were different because the goal of this study was to induce submaximal physical fatigue.

Initially, the warm-up was performed on a wattbike with zero resistance followed by a fatigue protocol. The instructions given to the participants were,

> *"Cycle until you reach 15 (hard) on a 6–20 Borg scale of RPE. Maintain a pedaling rate of 50–60 rpm. If you experience any discomfort, dizziness, or loss of balance while cycling, stop, rest, and continue if you wish. The laboratory has the option of lying or sitting".*

Monitoring of sub-maximal fatigue protocol

Every minute, the HR, oxygen saturation, and RPE were recorded. According to ACSM, objective

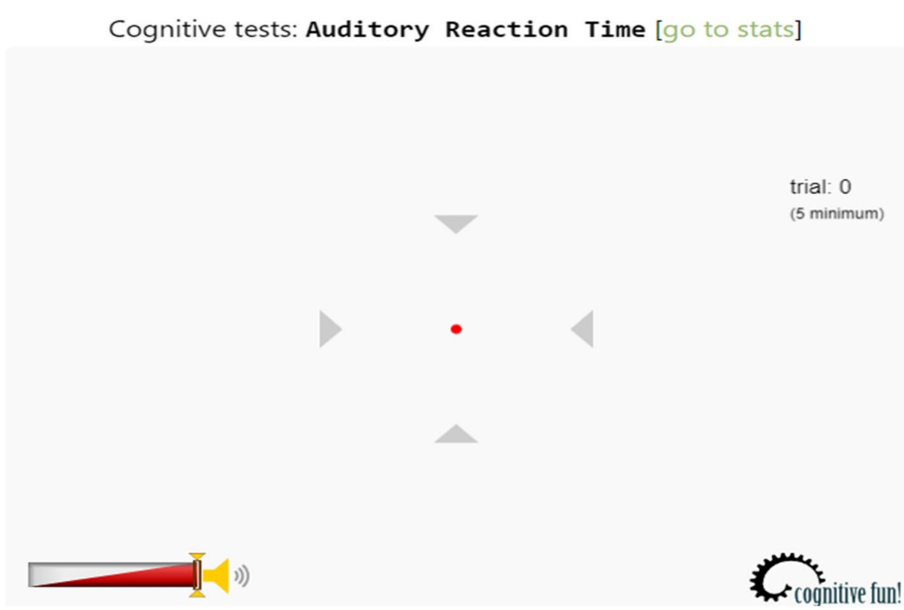

Fig. 2 Image of ART task. Reaction time test with auditory stimuli. Simply click when you hear the sound

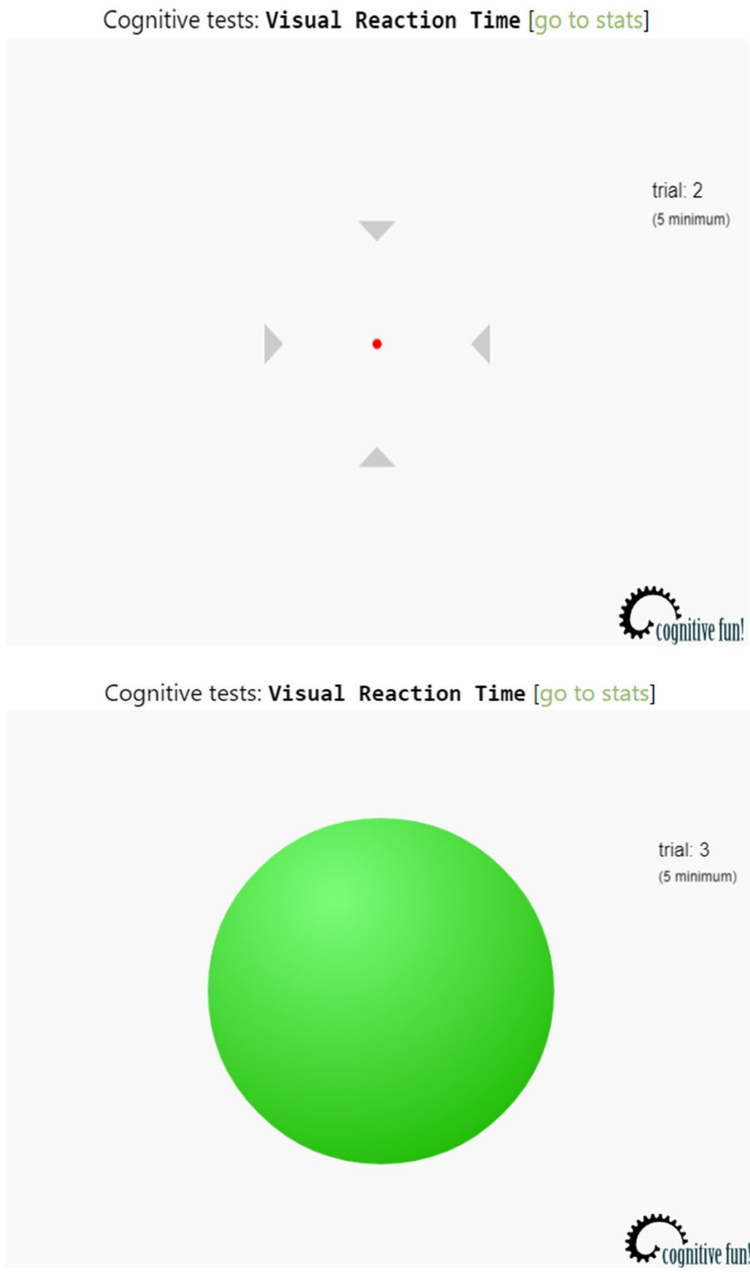

Fig. 3 Image of VRT task. Classic reaction time test. **Click when the green dot appears**. Reaction time is an important indicator of attention and a common measure used in more complex tasks. Measure and record your reaction times and compare them with your previous times as you practice! **Try to aim for below 250ms.**

measures such as HR were used to monitor fatigue in addition to the 6–20 Borg scale of RPE [40]. The age-predicted maximal heart rate was calculated using the formula [208-(0.7 × age)] because the study participants were healthy [26]. During the fatigue protocol, participants were not allowed to go beyond the sub-maximal range that is HR was less than 80% of HRmax. Furthermore, oxygen saturation was not permitted to fall below 85%.

Termination criteria of the sub-maximal fatigue protocol

1. Level 15 on the RPE scale [24].
2. If participants were unable to maintain the speed of the cycling between 50 and 60 rpm.
3. If participants crossed the sub-maximal range of HR.

Following the fatigue protocol, five RT (ART in the first session and VRT in the second session) readings were

Fig. 4 Wattbike (cycle ergometer)

taken twice: once immediately after the fatigue protocol (POST-0) and again 15 min later (POST-15). HR, RPE, and oxygen saturation were also measured at POST-0 and POST-15. Between POST-0 and POST-15, the participants were instructed to remain seated on the chair without engaging in any other physical activity.

Although five readings of RT were taken, only the mean of the middle three RT scores were taken to improve study precision and reliability estimates by reducing error variance [21].

Statistical analysis

All data collected was analyzed using the IBM Statistical Package for Social Sciences (SPSS) 27.0.1. SPSS was used to produce descriptive statistics for demographic, HR, and RT data. If the data was normally distributed, the mean, standard deviation, and range were presented; otherwise, the median and interquartile range were shown. The data's normality was determined visually with a histogram and statistically with the Shapiro–Wilk tests.

The dependent variable (RT) was measured on a ratio scale. As a result, if the data was normally distributed, a parametric test was selected to analyze it, as a non-parametric equivalent test [21]. For each dependent variable (ART and VRT), one-way repeated measures analysis of variance (ANOVA) was used if the data was normally distributed, or Friedman's ANOVA if it was not [12, 15]. According to Keselman and Rogan [41], a high *F*-ratio (derived from repeated measures ANOVA) indicates that the differences observed were caused by measurement conditions rather than random factors.

The assumption of sphericity was also checked using Mauchly's test. The Mauchly test results indicate significant differences and failure to meet sphericity, requiring a Greenhouse–Geisser correction for valid *F*-ratio, and no correction for insignificant results.

When a significant interaction was revealed ($p < 0.05$), post hoc tests such as the Bonferroni test were performed to control for family-wise error [21].

The difference between POST-0 and PRE values in all participants was calculated separately for ART and VRT to compare the change in RT due to submaximal fatigue between ART and VRT. If the data was normally distributed, a paired *t* test was used to compare the differences; otherwise, a Wilcoxon-signed rank test was used.

Results

Demographic data

Eighteen participants (9 males and 9 females) took part in this study. Table 2 consists of descriptive characteristics of the participants.

All participants abstained from caffeine, alcohol, and nicotine, as well as from strenuous physical activity and fasting for 24 h before the study. They self-reported an average of 7.1 h of sleep a night before the study, indicating an optimal level of arousal.

Sub-maximal physical fatigue in both sessions

There were no symptoms of dizziness or syncope during or after the fatigue protocol. All participants stopped the fatigue protocol at RPE 15. The saturation level of oxygen did not fall below 95%.

Table 2 Demographic data of the participants

	Mean	Standard deviation	Median	Interquartile range	Minimum	Maximum	Range
Age (years)	24	2	24	2	19	27	8
Height (cm)	167.5	12.9	171	25.1	146.7	184	37.3
Weight (kgs)	66.5	12.6	67.1	16.3	39.2	85	45.8
BMI (kg/m^{-2})	23.57	2.96	23.44	3.27	18.21	29.87	11.66

HR data of ART session in Fig. 5, self-reported RPE scores of participants, and repeated measures ANOVA results confirmed sub-maximal physical fatigue after cycling which was recovered within 15 min after the termination of cycling.

HR data of VRT session in Fig. 6, self-reported RPE scores of participants, and repeated measures ANOVA results confirmed sub-maximal physical fatigue after cycling which was recovered within 15 min after the termination of cycling.

Figure 7 confirmed that both sessions experienced similar submaximal physical fatigue, as there was no significant difference in mean HR at all three-time points.

Descriptive and statistical analysis of RT

ART: PRE, POST-0, and POST-15

Descriptive statistics of the ART Table 3 displays the descriptive statistics for the ART. Increased ART at POST-0 compared to PRE indicates slower RT, whereas decreased ART at POST-15 compared to POST-0 indicates faster RT at recovery.

Testing for the normality of the ART data According to the Shapiro–Wilk test, the data for PRE, POST-0, and POST-15 ART were not normally distributed, as shown in Table 4. As a result, Friedman's ANOVA was employed for inferential analysis.

Friedman's ANOVA Friedman's ANOVA revealed a significant difference between the three values, with a P value of 0.015 (Table 5).

Post hoc analysis (Table 6) revealed a significant difference between POST-O and PRE ART ($P=0.002$), as well as between POST-15 and POST-0 ART ($P=0.010$), but not between POST-15 and PRE ($P=0.647$).

Overall, after submaximal fatiguing exercise, ART was significantly slower. However, after 15 min of rest, it returned to normal.

VRT: PRE, POST-0, and POST-15

Descriptive statistics of the VRT

Table 7 displays the VRT's descriptive statistics. Increased VRT at POST-0 compared to PRE indicates

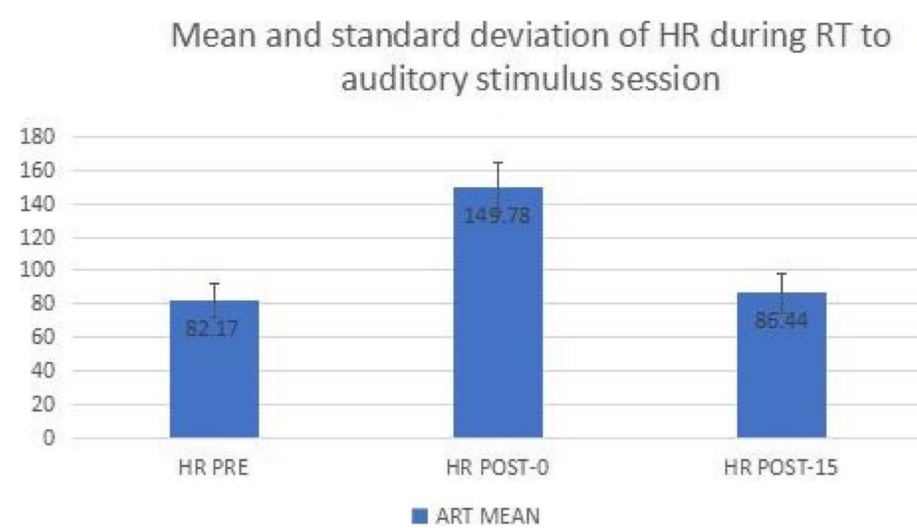

Fig. 5 Mean and Standard deviation of HR during ART session (error bars indicate standard deviation)

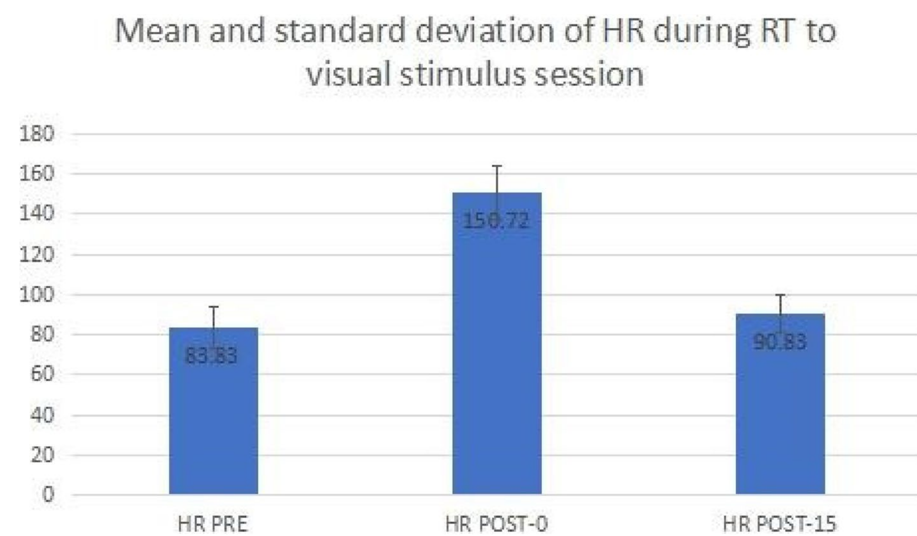

Fig. 6 Mean and standard deviation of HR during VRT session (error bars indicate standard deviation)

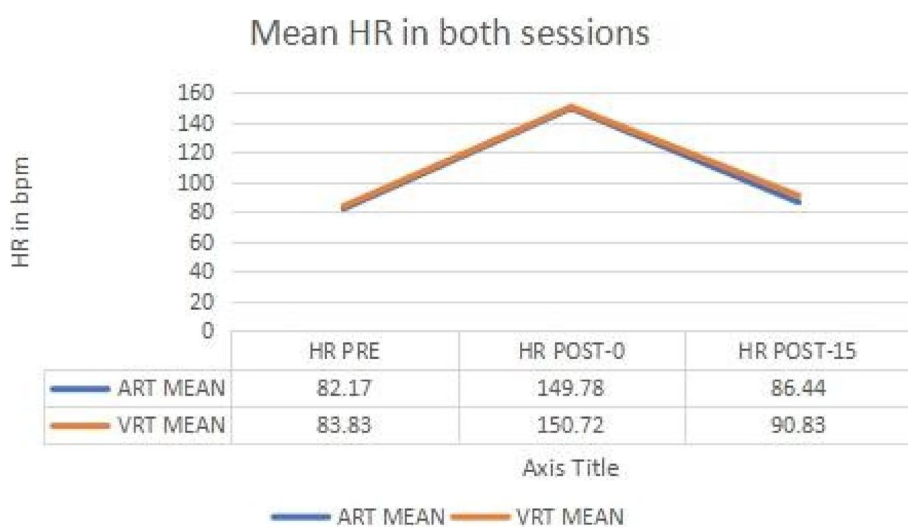

Fig. 7 Mean HR at PRE, POST-0, and POST-15 in both sessions

Table 3 Descriptive statistics of the ART

	Mean	Std. deviation	Percentiles		
			25th	50th (median)	75th
ART PRE (ms)	283.28	48	254.08	276.83	305.5
ART POST-0 (ms)	323.19	65.39	277.5	297.83	360.17
ART POST-15 (ms)	288.94	57.72	251.58	275.17	303.92

Table 4 Results of the Shapiro–Wilk test of ART data

	Tests of normality		
	Statistic	df	Significance
ART (PRE)	0.83	18	0.004
ART (POST-0)	0.842	18	0.006
ART (POST-15)	0.799	18	0.001

Table 5 Results of Friedman's ANOVA of ART

Test statistics[a]	
N	18
Chi-square	8.444
df	2
Asymp. Sig	**0.015**

[a] Friedman test

Table 6 Pairwise comparisons for ART

Test statistics	ART (POST-0)-ART (PRE)	ART (POST-15)-ART (POST-0)	ART (POST-15)-ART (PRE)
Asymp. Sig. (2-tailed)	0.002	0.010	0.647

Table 7 Descriptive statistics of the VRT

	Mean	Std. deviation
VRT PRE (ms)	334.61	42.66
VRT POST-0 (ms)	401.38	83.12
VRT POST-15 (ms)	328.56	38.51

Table 8 Results of Shapiro–Wilk test for VRT

	Tests of normality		
	Statistic	df	Significance
VRT(PRE)	0.181	18	0.124
VRT (POST-0)	0.192	18	0.078
VRT (POST-15)	0.186	18	0.099

slower RT, whereas decreased VRT at POST-15 compared to POST-0 indicates faster RT at recovery.

Testing for the normality of the VRT data

According to the Shapiro–Wilk test, the data for PRE, POST-0, and POST-15 VRT were normally distributed, as shown in Table 8. For inferential analysis, a parametric test (repeated measures ANOVA) was used.

Repeated measures ANOVA

Table 9 shows the violation of the sphericity assumption for the VRT values using Mauchly's test of sphericity ($W = 0.590$, $\chi 2 = 8.435$; the P value was less than 0.05, where W is Mauchly's W and $\chi 2$ is a chi-square). As a result, the Greenhouse–Geisser test was applied, and the corrected F values of a within-subject ANOVA analysis were Df = 1.419, $F = 17.594$, and $P < 0.001$, where Df represents the degree of freedom, F represents the F ratio, and P represents the probability level (Table 10).

Table 10 shows a significant difference between the three VRT values (PRE, POST-0, and POST-15) because the P value of a corrected Greenhouse–Geisser effect was less than 0.05. According to Keselman and Rogan [41], a high F ratio indicates that the study protocol, rather than random factors, is the cause for the change in outcome measurement. As a result, in the current study, sub-maximal physical fatigue caused a change in VRT.

According to the Bonferroni test (Table 11), there was a significant difference between POST-O and PRE VRT ($P = 0.001$), as well as between POST-15 and POST-0 VRT ($P = 0.001$), but not between POST-15 and PRE ($P = 1.0$).

Overall, VRT was significantly slower after submaximal fatiguing exercise. After 15 min of rest, it returned to baseline.

Table 9 Results of Mauchly's test of sphericity of VRT

Mauchly's test of sphericity[a]							
Within subjects effect	Mauchly's *W*	Approx. chi-square	df	Sig	Epsilon[b]		
					Greenhouse–Geisser	Huynh–Feldt	Lower-bound
VRT	.590	8.435	2	0.015	.709	.755	.500

Table 10 Corrected *F* values of VRT

Source	*F*	Significance (*P*)
Greenhouse–Geisser	17.594	0.000

Comparison in change in RT (POST O-PRE) between ART and VRT

The effect of submaximal physical fatigue is indicated by a change in RT from PRE to POST-O (POST 0-PRE).

Table 11 Bonferroni test for VRT at PRE, POST-0, and POST-15

RT	RT	Significance
VRT PRE	VRT POST-0	**0.001**
	VRT POST-15	1.000
VRT POST-0	VRT PRE	**0.001**
	VRT POST-15	**0.001**
VRT POST-15	VRT PRE	1.000
	VRT POST-0	**0.001**

Descriptive statistics

The difference between POST-0 and PRE (POST 0-PRE) was calculated for each participant for the ART and VRT. The mean change in ART and VRT due to sub-maximal fatigue was 39.91 ms and 66.78 ms, respectively, as shown in Fig. 8.

Testing for normality of data for comparison between ART and VRT

Shapiro–Wilk test showed a normal distribution of data as seen in Table 12.

Because the data was normally distributed, a paired t-test was used to compare the fatigue effects of ART and VRT.

Paired t test

Positive ART and VRT values indicate that the mean value of POST-0 RT was greater than the PRE RT, indicating that participants took longer to respond to both auditory and visual stimuli after submaximal physical fatigue. The parametric paired *t*-test (Table 13) revealed no statistically significant difference in the mean of change between VRT and ART ($P = 0.156$).

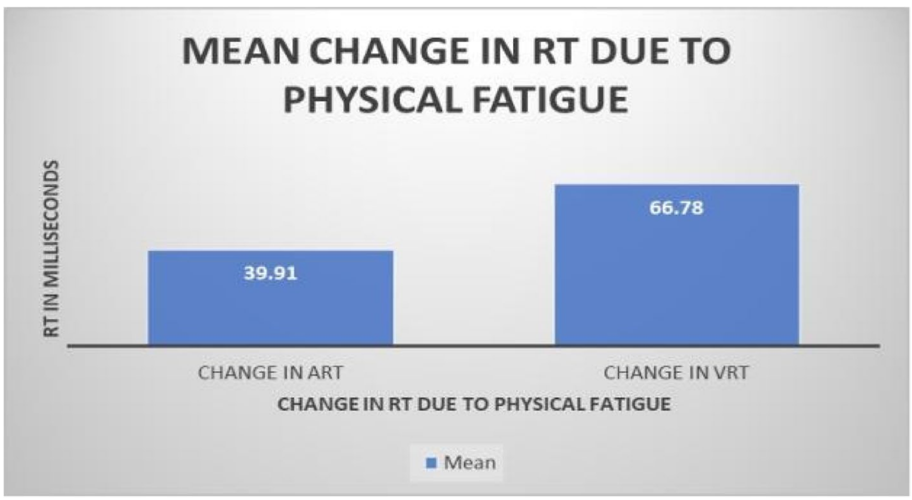

Fig. 8 Mean change in ART and VRT due to sub-maximal physical fatigue

Table 12 Results of the Shapiro–Wilk test for the change in RT due to sub-maximal physical fatigue

	Tests for normality		
	Statistic	df	Significance
Change in ART	0.938	18	0.272
Change in VRT	0.915	18	0.104

Table 13 Results of paired *t* test

Paired samples test								
	Paired differences					*t*	df	Sig. (2-tailed)
	Mean	Std. deviation	Std. error mean	95% confidence interval of the difference				
				Lower	Upper			
Change in ART-Change in VRT	−26.87	76.85	18.11	−65.09	11.35	−1.483	17	**0.156**

Overall, the effects of physical fatigue were not significantly different between the ART and VRT. Furthermore, for the sample studied, sub-maximal physical fatigue had a similar effect on ART and VRT.

Discussion

The study aimed to find the effects of sub-maximal physical fatigue on ART and VRT. According to our study's findings, ART and VRT are slower due to sub-maximal physical fatigue, which returns to baseline after 15 min of rest. Furthermore, this study found that submaximal physical fatigue affects ART and VRT equally. In contrast to the current study, Morrison et al. found that fatigue did not affect the VRT of the younger participants [17]. In addition, Coco et al. demonstrated that the fatigue after cycling at 80% of VO2max slowed the VRT, but cycling at 60% of VO2max had no effect [15]. Similarly, McMorris and Keen in 1994 found that the VRT was slow when cycling at 100% rather than 70% maximal power output on a cycle ergometer [42]. Different results in different studies may be due to differences in fatigue intensity, RT measurement timing, and other confounding factors which are discussed below.

Fatigue intensity

According to Ozdemir et al. [12], the effect of fatigue on RT depends on the intensity of the fatigue. The intensity of fatigue, however, was determined by power output by McMorris and Keen [42] and VO2max and blood lactate levels by Coco et al. [15]. The current study suggests that the fatigue produced by cycling at 60% of VO2max in the study by Coco et al. [15] and at 70% of maximal power output in the study by McMorris and Keen [42] was not equal to the sub-maximal physical fatigue of RPE 15 (60–80% HRmax), exhibiting different results. This is supported by the mean RPE of the participants at the end of the fatigue protocol in McMorris and Keen's study [42], which was 11.75 rather than 15 as in the current study. It can be assumed that the RPE of 11.75 was insufficient to cause a change in VRT. Morrison et al. found that 15 min of walking-induced fatigue slowed VRT in older but not younger participants [17]. This is because the participants were given 5 min of rest time during the fatigue protocol, which may have resulted in partial fatigue recovery in younger participants [18].

RT assessment post-fatigue

The differences in results could also be due to differences in the timing of the RT assessment post-fatigue protocol. In the current study, ART and VRT were evaluated immediately following the fatigue protocol. Morrison et al. [17] and Coco et al. [15] may have had a delay in RT measurement because other tests were assessed alongside RT and the order of the assessments was not specified. Partial recovery from central and peripheral fatigue occurs within a few minutes [18], which could explain the insignificant results exhibited in the study by Coco et al. [15] and Morrison et al. [17].

Confounding factors

Another reason could be that none of the three studies mentioned caffeine consumption control by participants [15, 17, 42]. Even 5 mg of caffeine taken 1 h before the test can improve RT by 11.9–29% because it has positive effects on nerve conduction and transmission [14]. Furthermore, it improves cerebral oxygenation and delays fatigue sensation [14]. In all three studies, these factors could have resulted in less fatigue intensity following the fatigue protocol.

VRT was also affected in other studies, similar to the current study [12, 13, 16]. However, the fatigue induced in those studies was of maximal rather than sub-maximal intensity. According to Krüger et al. [43], short-duration high-intensity exercise on an ergometer causes peripheral fatigue rather than central fatigue. As a result, results are not comparable. Another factor in the study by Ozdemir et al. [12] was that the participants did a 15-min squeezing exercise on a hand-held dynamometer before the study. Because the RT task required hand muscles, fatigued hand muscles could have contributed to the affection of RT scores. Ozdemir et al. [12] did not assess RT before the fatigue protocol, making it difficult to rule out the possibility of a cross-over effect.

Physiological rationale behind the effects of sub-maximal fatigue on ART and VRT in the current study

Slower RT could be due to an increase in pre-motor or motor time [44]. An increase in pre-motor time indicates cognitive delays, whereas an increase in motor time indicates motor delays in total RT. Premotor and motor time were not measured separately because this study used computer-based RT measurement rather than surface electromyography (EMG). EMG studies revealed premotor time as the cause of delayed RT [45, 46], whereas Le Mansec et al. in 2019 [44] revealed motor time as the cause of delayed RT. The findings of the studies by Ando et al. [45] and Ando et al. [46] are more relevant to the current study. This is because the participants had similar HR and RPE after the sub-maximal fatigue protocol on the cycle ergometer. Additionally, participants were the same age as in the current study. Furthermore, premotor time accounts for a higher proportion of total RT (87.9%) [44]. In conclusion, it is reasonable to believe that increased pre-motor time (cognitive delay) rather than motor delay was the primary cause of the significantly slower ART and VRT in the current study. However, further research using EMG is needed to confirm this.

Increased pre-motor time (cognitive delay) may be associated with central fatigue and decreased cerebral oxygenation in brain regions that control stimulus reactions [36, 47]. This decreased cerebral oxygenation in the prefrontal and frontal cortex following submaximal fatigue has been confirmed in studies [46, 48]. The prefrontal and frontal cortex are important for RT [7]. As a result of fatigue, blood flow in the brain may divert away from the prefrontal or frontal cortex towards other areas.

Sudo et al. in 2017 discovered that decreased cerebral blood flow alters neurotransmitter turnover of dopamine, noradrenaline, serotonin, adrenocorticotropic hormone, and cortisol, slowing nerve conduction and processing time [48]. This slower processing time impairs the ability of frontal cortex association fibers and auditory and visual neuronal pathways to process nerve impulses [36], affecting pre-motor time and thus delaying RT.

Coco et al. [15] and Coco et al. [16] investigated the effects of fatigue recovery on VRT by measuring VRT 15 and 10 min after a fatigue protocol on a cycle ergometer. In both studies, VRT returned to baseline, as in the current study. According to the above studies, the recovery of RT is due to the recovery of elevated blood lactate levels following the fatigue protocol. However, the results cannot be directly compared due to differences in fatigue protocol intensity, lack of consideration of RPE, and assessment of other cognitive tests in addition to RT in the two studies. Hence, further research is required.

There have been no previous studies comparing the effects of fatigue between ART and VRT. It is possible that submaximal physical fatigue affects the time required to process sensory (auditory or visual) information equally in the current study. In the current study, sub-maximal physical fatigue may have influenced neural signal transmission and processing time proportionally. More research using electroencephalography (EEG) and transcranial magnetic stimulation (TMS) is needed to investigate the effects of fatigue on the mechanisms of ART and VRT.

Strengths of the study

To avoid gender bias, both male and female participants were equal in number. Caffeine, smoking, alcohol, vigorous exercise, and motivation were all controlled for. To avoid a carryover effect, ART and VRT were evaluated in two separate sessions. In addition, conducting two different sessions also helped to assess RT quickly post fatigue which was unique to this study.

Limitations

The involvement of a single researcher for data collection, analysis, and interpretation, enhances the risk of researcher bias. This study did not take into account the participants' physical fitness or intellectual status, which influences RT. To demonstrate the effects of fatigue on RT, this study did not use precise methods such as maximal oxygen consumption (VO2 max), blood lactate levels, or EMG. There is a possibility of a learning effect because there was no randomization in RT assessment because ART was mentioned in the first session and VRT was mentioned in the second session for all participants. Other limitations include convenience sampling and a smaller sample size, which may have affected the results' generalizability.

Clinical relevance

The clinical implications of this study are in stroke rehabilitation. For example, RT is already affected in stroke patients. Because RT is affected post-fatigue, this can cause balance problems in stroke patients who are fatigued during stroke rehabilitation. Stronger reactions are required during balance rehabilitation. Therefore, clinicians may consider giving rest to stroke patients after fatiguing exercise. This will improve training outcomes during the balance training.

Conclusion

The sub-maximal physical fatigue protocol causes delay in ART and VRT which recovers in 15 min. There was no statistically significant difference between the effects of ART and VRT. The study's findings have clinical implications for balance training in stroke rehabilitation. The results of this study will help therapists to plan balance training for patients with stroke. Slower simple RT causes balance issues leading to falls and because sub-maximal physical fatigue slows RT it may lead to falls. Hence, balance training should not be performed immediately after exercise rehabilitation because there is a risk of falling due to RT affection. Similar studies can be conducted in the future with participants fatigued on an arm ergometer or treadmill, which are also common modes of exercise in stroke rehabilitation. Similarly, the effect of mental fatigue on ART and VRT can be studied.

Abbreviations

RT	Simple reaction time
VRT	Visual reaction time
ART	Auditory reaction time
RPE	Rating of perceived exertion
HR	Heart rate
VO_{2max}	Maximal oxygen consumption
HR_{max}	Maximum heart rate
SPSS	Statistical Package for the Social Sciences
ANOVA	Analysis of variance
EMG	Surface electromyography
PAR-Q	Physical Activity Readiness Questionnaire

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Authors' contributions
SJ and SD contributed to the conception of the study and study design. SJ was responsible for the data collection and data analysis. SJ was responsible for writing this manuscript. SJ and SD critically revised the draft. All authors read and approved the final draft.

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Availability of data and materials
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
The current study was approved by Cardiff University's School of Healthcare Sciences Ethical Research Committee (REC935). The participant information sheet was emailed to the participants, and they were given 48 h to decide whether to participate in the study and sign the consent form on the data collection day. The participant information sheet detailed the study's benefits, risks, and procedures, as well as the amount of time required of participants. They were given the option to withdraw from the study at any time, except after data collection. To maintain their dignity and privacy, the participants were given changing spaces while wearing the chest straps of the Polar HR monitor (used to monitor and assess HR).

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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