The effect of dehydration on cognitive abilities

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Abbreviations

DSM-5	Diagnostic and Statistical Manual of Mental Disorders 5
ms	Milisenconds
CI	Confidence interval
ML	Maximum Likelihood
MM	Method of Moments
R	Robust method
Q-Q plot	Quantile-Quantile plot

Abstract

Water consumption is crucial for human life and survival. It is vital to have a balance between water loss and water consumption. If this balance is not maintained and a body loses more water than it consumes it is called dehydration (*Greenleaf-1991*, n.d.)]. Numerous experiments have researched the effects of dehydration on the cognitive abilities. However, most of these researches are focused on high-risk groups (Pross, 2017). Therefore, the aim of this study was to investigate the short-term effects of dehydration on different cognitive domains in adults. Dehydration was obtained by exercising in a sweatsuit, where the participants were not allowed to drink fluids. After dehydration was obtained, five cognitive domains were tested: learning and memory, language, perceptual-motor function, executive function, and complex attention. However, only a maximum of 1.2% dehydration (body-weight loss) was achieved using this method. Most of the time this mild dehydration did not seem to have a negative effect on the performance on the listed domains. However, various results were obtained per participant when looking at a specific domain. In general, this work illustrates that achieving a dehydration level of at most 1.2% is not enough to significantly affect your mental abilities.

Significance statement

This research aims to provide new insights into the effects of dehydration on cognitive functioning. Most of the research done on this subject focuses on a ‘high risk’ group for dehydration like children or elderly, little research has been done on the cognitive effect on healthy adults. Through this research the negative effects of dehydration, and how easy it is to dehydrate to a level in which cognitive functions are impaired, will be underscored. Reaffirming the importance of informing the general public about the negative effects of dehydration and how easy it is to dehydrate to a level in which cognitive functions are impaired. Leading ultimately to a healthier, more productive society.

Introduction

Dehydration

Water consumption is crucial for human life and survival. At infancy about 75% a human body consist of water, which decreases to about 60% after puberty (*Anci-2004*, n.d.). It is vital to have a balance between water loss and water consumption. Body fluids are normally lost through sweat, tears, urinary system, respiratory or gastrointestinal system (Barley et al., n.d.). The required amount of water intake per day depends on body weight, age, daily activities and metabolism (Jéquier & Constant, 2010a). Severe alteration in the water level of body can lead to various medical conditions such as dehydration and overhydration (Popkin, D'Anci, et al., 2010). Some age groups including infants and elderlies face a higher risk of dehydration (Begum & Johnson, 2010; Jéquier & Constant, 2010b). Gender however is not considered as a risk factor (Białecka-Dębek & Pietruszka, 2019).

Dehydration occurs when the body loses more fluids than it consumes (*Greenleaf-1991*, n.d.). It is classified into three categories, which differ in the amount of salt loss. If the body loses water and salt at an equal rate, it is called isotonic dehydration. When the body loses more water than salt, it is called hypertonic dehydration, while hypotonic dehydration is the opposite (Popkin, D'anci, et al., 2010). Hypertonic dehydration is often caused by excess pure water loss occurs through the skin, lungs, and kidneys, while hypotonic dehydration is mostly caused using diuretics. Several factors cause dehydration e.g., exercise, heat, or little water consumption (Lieberman, 2012). There are three main methods for determining hydration status, firstly, invasive techniques like neutron activation analysis. Secondly, moderately invasive techniques including blood, salivary, and urine tests. Lastly, non-invasive approaches such as tear osmolality, body mass, bioimpedance analysis (Barley et al., n.d.)

Numerous experiments and studies have conducted to investigate dehydration impacts on cognitive abilities (Cian et al., 2001; Tomporowski et al., 2007; Zhang et al., 2019). It has been reported that several aspects of cognitive abilities, such as concentration, short-term memory, long-term memory and alertness can be affected in case of mild to severe dehydration (Popkin, D'anci, et al., 2010; Zhang et al., 2019).

Cognitive tests

The neurocognitive domains can be defined in six key domains, according to the Diagnostic and Statistical Manual of Mental Disorders 5 (DSM-5) (Sachdev et al., 2014). These domains are shown in figure 1. The 5 cognitive domains that were tested in this project were: language, learning and memory, complex attention, executive function and perceptual-motor function. For each domain a different test was taken. While each test focusses on their own domain, cognitive functioning is a combination between different neurocognitive processes, so there exists overlap between the tests.

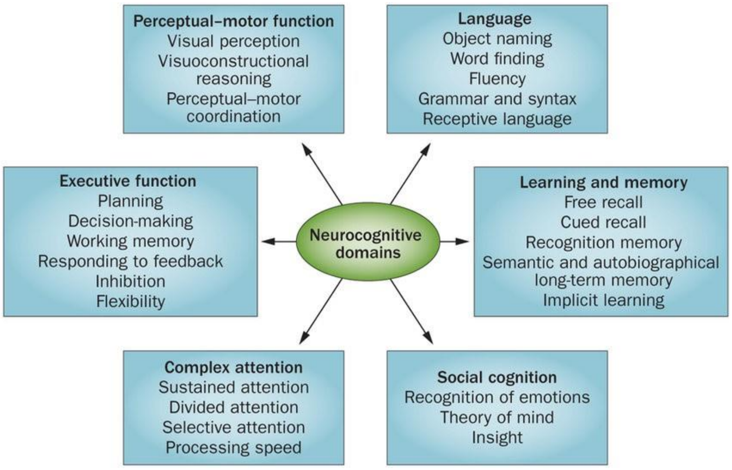

Figure 1: The six neurocognitive domains and subdomains of humans, according to DSM-5 from: Sachdev, Perminder & Blacker, Deborah & Blazer, Dan & Ganguli, Mary & Jeste, Dilip & Paulsen, Jane & Petersen, Ronald. (2014). Classifying neurocognitive disorders: The DSM-5 approach. Nature Reviews Neurology.

Learning and memory

Since the digit span task is such a well-established memory span test, this was selected to evaluate the domain of Learning and Memory (Jones & Macken, 2015). During the task the participant is presented with a sequence of numbers. If the participant can repeat the sequence, a longer sequence is presented. This continues until the participant cannot repeat the sequence without error.

Complex attention

To evaluate the domain of complex attention the flanker test was selected. Also known as the Eriksen flanker task and published in 1974 by Barbara A. Eriksen and Charles W. Eriksen (Eriksen & Eriksen, 1974). It is a popular test for complex attention and there are many variants of the original. The Flanker task is a set of response inhibition tests where a target stimulus is presented flanked by irrelevant stimuli. In the traditional flanker test, three types of stimuli are used. Congruent stimuli are flankers that call for the same response as the target or may be identical. Also referred to as the compatible condition. Incongruent stimuli are flankers call for the opposite response as the target. Also referred to as the incompatible condition. Natural stimuli are flankers that neither call for the same result as the target, nor evoke a conflicting response.

Executive functioning

To evaluate the domain of ‘Executive function’ we decided to look at inhibition. For this purpose, we selected the ‘Stop Signal task’. In this task you are asked to respond to a signal as quick as you can, except when you are presented to the stop signal, after the initial signal. Compared to ‘standard’ go/no-go tasks this is considerably more difficult because you need to stop a response you might have already initiated (Verbruggen & Logan, 2008).

Perceptual-Motor function

The Stroop task, named after John Ridley Stroop, is one of the most well-known psychological experiments. The Stroop effect is described as the delay in congruent and incongruent stimuli (MacLeod, 1991). The basic task demonstrates this effect by having a subject name the colour of the font a word is written in. A congruent stimulus would be for instance 'RED' written in red while an incongruent stimulus would be 'RED' written in blue.

Language

To assess verbal fluency, as part of the language domain, an adaptation of the Controlled Oral Word Association Test was performed. This test is used to measure verbal fluency and is a subset of the Multilingual Aphasia Examination (Kreutzer et al., 2011, p. 768).

Research question

As previously mentioned, numerous experiments and studies have conducted to investigate dehydration impacts on cognitive abilities (Cian et al., 2001; Tomporowski et al., 2007; Zhang et al., 2019) However, here are inconsistencies in the results of different articles based on the duration of the experiment and the tested age group (Drozdowska et al., 2020a; Zhang et al., 2019). Additionally, there seems to be a shortage of research related to the relationship between dehydration and cognitive abilities in adults (Drozdowska et al., 2020).

Consequently, the aim of this study is to investigate the short-term effects of dehydration on different cognitive domains in adults: language, executive function, complex attention, perceptual-motor function and, language and learning (Social cognition domain will not be tested in this project as there are not the necessary materials and test to test this ability accurately).

Since the cognitive abilities can be divided in different domains and each of them will be tested independently. Therefore, each test has its own hypothesis, which are as follows:

- Learning and memory domain:
  We expect the recall accuracy to decrease under the influence of dehydration.

- Complex attention domain:
  We expect the selective attention accuracy to decrease and the reaction time to increase under the influence of dehydration.

- Executive function domain:
  We expect the accuracy to decrease and the reaction time to under the influence of dehydration.

- Perceptual-motor function domain:
  We expect the psychomotor reaction time in to increase and accuracy to decrease under the influence of dehydration.

- Language domain:
  We expect the verbal production in words per second to decrease under the influence of dehydration.

Material and Methods

Participant characteristics

For this study five participants - three males and two females ranging from age 23 – 31 years old with different ethnicities were selected. All of them were students of the Faculty of Life science and Technology at the Hanze University of Applied Sciences (Table 1).

Table 1: Participant details

Pseudonym	Age	Sex	Medical background
Red	31	Female	Nothing to declare
Green	26	Female	Nothing to declare
Orange	23	Male	Nothing to declare
Pink	27	Male	Attention Deficit Hyperactivity Disorder
Blue	29	Male	Nothing to declare

Experimental design

To assess the effect of dehydration on cognitive abilities the participants performed four workout sessions divided into two experiments, each with one repeat. Giving as a result, two dehydration sessions and two control sessions. In both cases, the participants followed a predesigned 40-minute spinning session to dehydrate the participant (*40 Minute Sprint Intervals: Sufferfest's "Equalizer" | Indoor Cycling Workout - YouTube*, n.d.). In the dehydration session, the participant was not allowed to drink any water/liquid while exercising, whereas during the control, the participant was allowed to drink water *ad libitum*. In all the sessions the participants worn a sweat suit, which in combination with the exercise, was used to reach rapid dehydration.

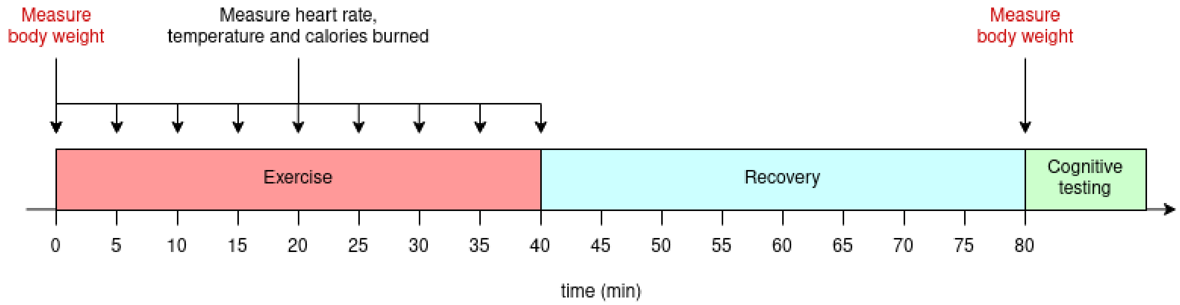

Figure 2: Flow chart of the dehydration and control workout sessions. The exercise, recovery and cognitive testing stages are shown in red, blue, and green, respectively. The times when the health parameters were tested are indicated by arrows.

The participant was weighed using an *OMRON Body Composition Monitor BF511* before the exercise and after the recovery period. Furthermore, in both groups every 5 minutes, personal health data was collected. Body temperature was measured in ear using a Bintoi® X100 thermometer and heart rate and calories burned were measured using a FitBit Charge 3 (Model FB409/FB410). After the exercise there was a recovery phase of 40 minutes in which the participants could rest. Hereafter, the cognitive abilities were tested according to 5 different domains. This process is visualised in figure 2. Difference in body mass at the beginning and end of the session was utilized to measure the amount of water lost during exercises.

Cognitive testing

For data collection, the PsyToolkit software was used (Stoet, 2010, 2016). To do the tests, the participant was placed in a quiet room with a laptop on which a browser was opened with the following tab: the Digit Span Test, Flanker Test, Stop Signal Test, Stroop Test, from PsyToolkit and an Excel sheet for noting down the results of each test. The participant was instructed to open each test in order and follow the instructions on the screen. After completing the test, the results were copied into the corresponding Excel sheet. When the four digital tests were completed, the participant was asked to notify the examinator so that he could perform the Verbal Fluency Test.

Digit Span Test

During this test the participant must remember a sequence of digits. First the sequence is shown, whereafter it must be repeated by clicking the right numbers on the screen. Initially, the sequence length is 2 and this increases when the participant remembered the sequence of that length correctly for 2 times in a row. The test stops when the participant made a mistake in repeating the sequence 2 consecutive times (*Digit Span Task*, n.d.).

Flanker Task

In the version used for this study, there are two types of stimuli used, congruent stimulus and incongruent stimulus. The participant responds to a series of 50 stimuli by pressing ‘A’ on the keyboard, if the stimuli ‘X’ or ‘C’ are shown, or 'L' if the stimuli ‘B’ and ‘V’ are shown (Flanker Task, n.d.).

Stop Signal Test

This test first has a training phase. During this training phase the participant should respond to a left or right green pointing arrow by pressing the right key. When a left arrow is shown, the ‘B’ key should be pressed and when a right arrow is shown, the ‘N’ key should be pressed. The participant must respond within 500 ms. The training phase consists out of 50 stimuli.

After the training phase a red circle may appear around the arrow after the arrow is already shown. If this red circle appears, the participant should not respond. The time when this red circle is shown after the arrow appears, is 50, 100 or 450 ms. This is chosen randomly. This phase consists of 40 stimuli (*Stop Signal Task*, n.d.).

Stroop Task

For this task the participant is presented with 40 written colours of which the ink colour either matches the written word or does not. The colours can be red, green, yellow and blue. The participant presses the buttons ‘R’, ‘G’, ‘Y’, or ‘B’ on the keyboard according to the ink colour shown, within two seconds (*Stroop Task*, n.d.).

Verbal Fluency Test

During the verbal fluency test the participant has 60 seconds to name as many English words starting with a letter, provided by the examiner. This was done for a total of 3 times, where 2 letters are consonants and 1 letter is a vowel. To avoid a learning effect, different vowels and constantan were chosen each repetition. The quantity of words is noted down. (Kreutzer et al., 2011 page 703 - 706)

Data Pre-processing and Analysis

All the data was initially recorded using excel. The data was then processed in Python 3.10.8 using the Python scientific stack. In particular, Pandas (v1.5.2), Numpy (v 1.24.1) and Scipy (v 1.10.0) libraries. Data visualisation was done with the use of the Bokeh (v 2.4.3), Matplotlib (v 3.6.2) and Holoviews (v 1.15.3) libraries. To present the data an interactive, online dashboard was made with the use of the Panel (v 0.14.2) library.

Statistical analysis was done in three stages using frequentist statistics methods such as Maximum Likelihood (ML), Method of Moments (MM), and Robust method (R). First, curve fitting and quantile-quantile plot (Q-Q plot) techniques are used to determine the type of distribution. Then, different methods like ML and MM are used to calculate the parameters of each distribution. Finally, a proper statistical test is implemented based on the distribution type to evaluate the hypothesis. In this article, three credible statistical tests were utilized, two-sample t-test, Wilcoxon signed-rank test, and two-sample z-test for proportion.

Results

Health data

The vital signs and body composition metrics of the five participants and their dehydration levels are described in the following tables. The averages of health data per participant in each session are shown in table 2. No large differences were seen in these measurements over four sessions. The heartrate, temperature, body weight, muscle percentage, fat percentage and fat percentage were measured during dehydration and control tests. Keep in mind that this data, except for the body weight, was only measured to keep track of the wellbeing of the participant. Therefore, more information and plots about these health data are provided in the supplementary part.

Table 2: Averaged health data per participant

participant	type	heartrate	temperature	body weight	muscle%	fat%
blue	control	148.22±13.59	35.58±0.59	73.05±0.91	37.7±0.5	21.55±0.81
	dehydration	153.11±10.97	34.42±1.03	72.88±0.29	37.65±0.57	21.62±0.66
green	control	122.22±17.45	36.91±0.25	60.45±1.08	37.98±0.17	23.22±0.5
	dehydration	117.67±15.02	37.21±0.19	60.85±0.69	38.02±0.61	23.35±0.4
orange	control	129.89±16.9	36.46±0.38	56.95±0.06	45.5±0.34	10.8±0.47
	dehydration	133.17±14.01	34.83±1.23	56.75±0.46	45.0±0.5	11.2±0.74
pink	control	123.17±10.1	37.12±0.13	77.35±0.19	34.33±0.84	29.65±1.22
	dehydration	132.72±11.6	35.88±0.93	76.6±0.49	34.83±0.22	28.8±0.4
red	control	146.94±12.5	36.54±0.18	79.93±0.05	22.15±0.17	48.15±0.24
	dehydration	147.5±17.88	34.71±1.24	79.4±0.33	21.42±0.19	48.98±0.32

As previously mentioned, the body weight loss is measured to calculate the dehydration percentage. These percentages of the dehydration and control sessions are shown in table 3. As shown in this table, regarding the dehydration session, all the participants in all sessions lost weight, except for the blue participant in session 1. A possible reason for this is speculated in the discussion. Furthermore, in a control session a participant sometimes gained weight and sometimes a participant lost weight.

Table 3: Weight loss percentage per participants per session

	Dehydration (weight loss %)		Control (weight loss %)	
	Session 1	Session 2	Session 1	Session 2
Blue	0.28	-0.68	0.41	-0.14
Green	-0.97	-0.66	-0.33	0.34
Red	-0.63	-0.63	0.0	0.13
Pink	-0.91	-1.17	-0.26	0.52
Orange	-1.22	-1.23	-0.18	-0.18

Cognitive tests

In the following sections, the obtained data of each test is visualised and statistically analysed.

Flanker test

The flanker test was used to evaluate the complex attention domain. This test can be divided into two parameters: reaction time and number of correct answers (accuracy).

Reaction time

It is expected that reaction time increases after dehydration. However, participants (orange and red) have less or equal reaction time in the control session compared to the dehydration session and were influenced negatively by dehydration. Other participants were not influenced by losing water. (See figure 3)

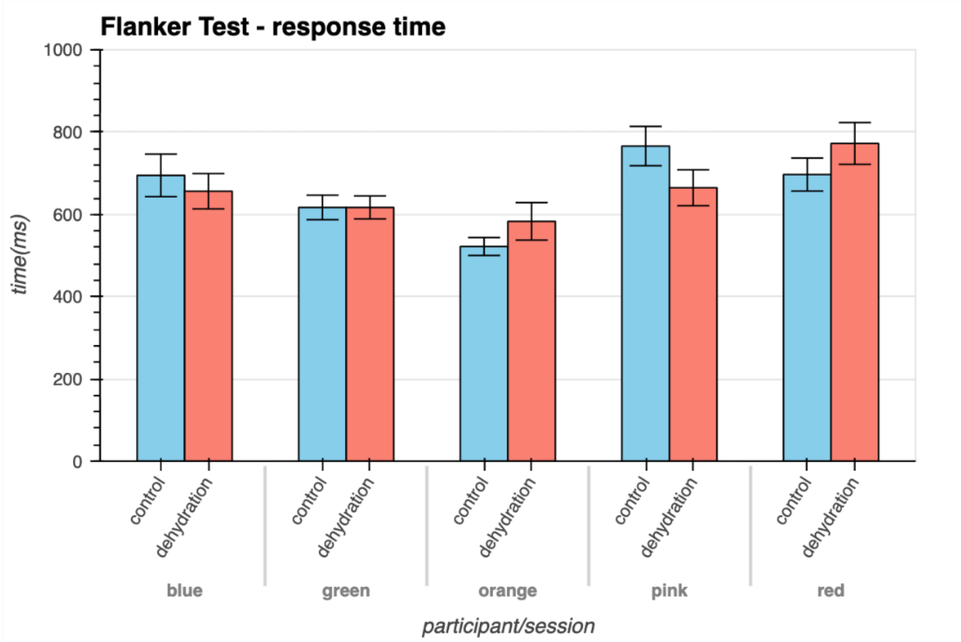

Figure 3: Bar plot of the average reaction time per participant, per session type in the Flanker test

The distribution of this data is illustrated in the figure below. As can be seen all participants follow a Gamma distribution. (see figure 4)

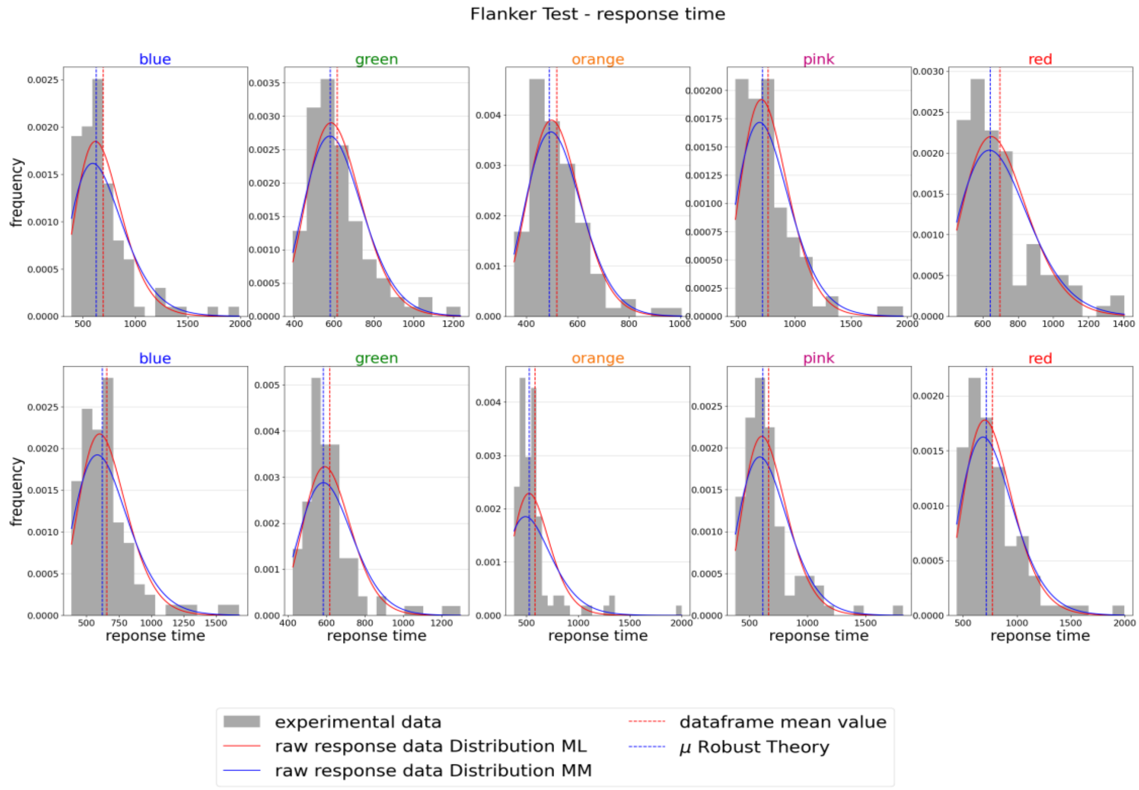

Figure 4: The distribution of the reaction time per participant for the flanker test

Based on the data distribution, two statistical tests are implemented to evaluate the hypothesis. First, a 2-sample T-test can be implemented on the data sets. T-test is the best nominate when there is sparse information about the sample i.e., unknown μ and σ. Second, Wilcoxon signed-rank test can be utilized since the control and dehydration data sets for each person are homogonous in terms of their shape. P value and stat value of the mentioned tests for each participant is presented in Table 4.

Table 4: T-test and Wilcoxon test parameters per participant for the flanker test

colour	blue	green	orange	pink	red
t_value_ttest	1.1214	0.0014	-2.4783	3.0705	-2.288
p_value_ttest	0.5659	0.7497	0.0036	0.5006	0.0058
stat_wilcoxon_test	2877.5	2640.0	1823.5	3538.0	1840.5
p_value_wilcoxon_test	0.5564	0.6731	0.996	0.5001	0.9954

For blue, green, and pink the hypothesis is rejected, there is not an increase when dehydrated. Also, even though Wilcoxon p value is higher than $\alpha = 0.05$ for orange and red, the p value of the T-test is roughly less than the α value. It shows that not only these two distributions do not share almost the same shape, but also the response time increased during the hydration experiment. Consequently, the hypothesis is approved for the mentioned participants.

Accuracy
It is expected that the answers accuracy decreases when dehydrated compared to the control. In figure 5, the average amount of correct answers is visualised in a bar plot. The number of correct answers in control and dehydration are for all participants approximately the same. There does not seem to be a pattern, which might be influenced by dehydration when compared to the control.

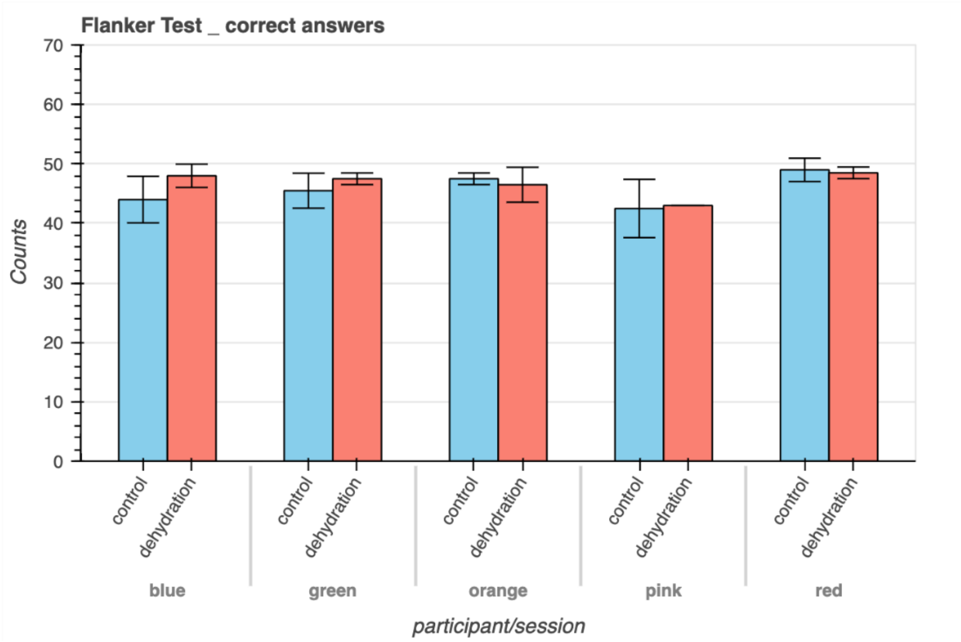

Figure 5: Bar plot of the average number of correct answers per participant, per session type in the flanker test.

This dataset consists of two values: correct and incorrect. Consequently, the binomial distribution is considered to describe this distribution best. Binomial distributions can be estimated by a Normal Distribution if $k \cdot P > 5$ and $k \cdot (1 - p) > 5$ where k is the sample size and p is the probability of being incorrect based on the number of incorrect answers per test per participant. Otherwise, it can be estimated by a Poisson Distribution (Bagui & Mehra 2017). Figure 6 depicts the accuracy distribution per participant per test.

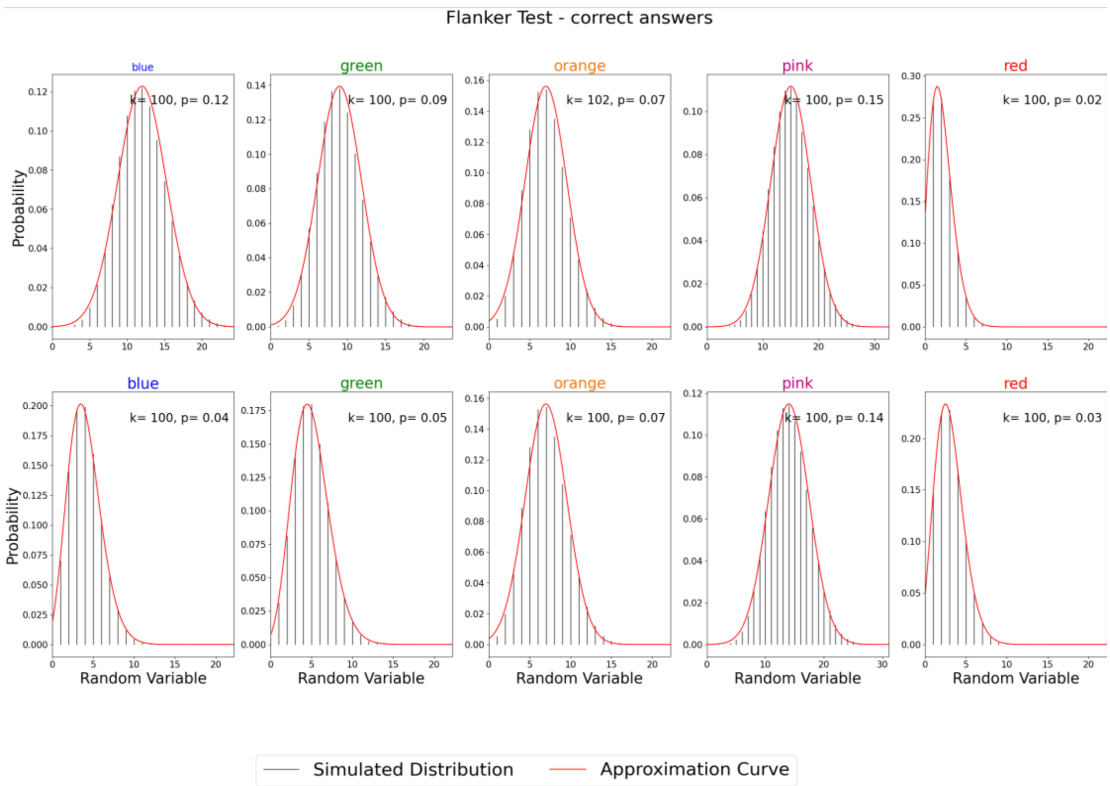

Figure 6: The accuracy distribution per participant for the flanker test

Based on the distribution of the data, 2-sample z-test for proportions is implemented to evaluate the hypothesis. The mentioned statistical test determines the difference of a specific parameter between two population. Consequently, it can be the best choice for evaluating the hypothesis. Stat value and p value are presented in Table 5 for each participant.

Table 5: Z-test parameters per participant for the flanker test

colour	blue	green	orange	pink	red
stat_ztest	2.0851	1.1085	-0.0384	0.2008	-0.4529
p_value_ztest	0.5093	0.5669	0.2423	0.7102	0.1627

For all the participants no significant change in the number of errors is detected, so the hypothesis is rejected, dehydration does not seem to affect the accuracy.

Stroop test

To assess the perceptual-motor function domain the stroop test was used. This test can again be divided into two parameters: reaction time and accuracy.

Reaction time

Here it was expected that the reaction time increases when a participant is dehydrated. As shown in Figure 7, almost all participants have more or equal reaction time in the control session than in the dehydration one. This means that the dehydration has had a positive effect on the reaction time. However, the red participant shows an increase in reaction time and therefor was negatively influenced by dehydration.

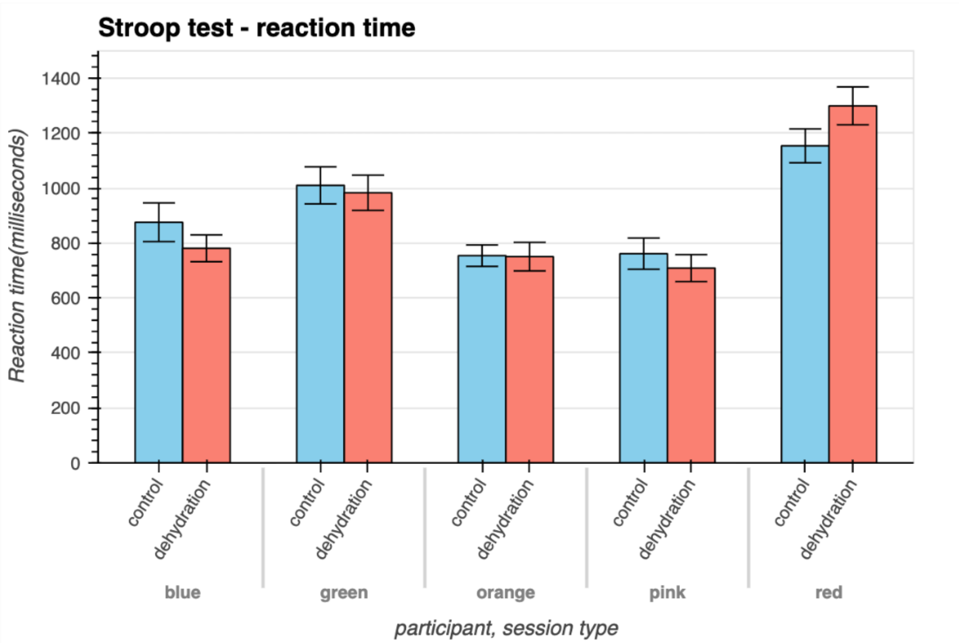

Figure 7: Bar plot of the average reaction time per participant, per session, per session type for the stroop test

Figure 8 illustrates the distribution of the reaction time data, per participant per test. These histograms follow roughly a normal pattern.

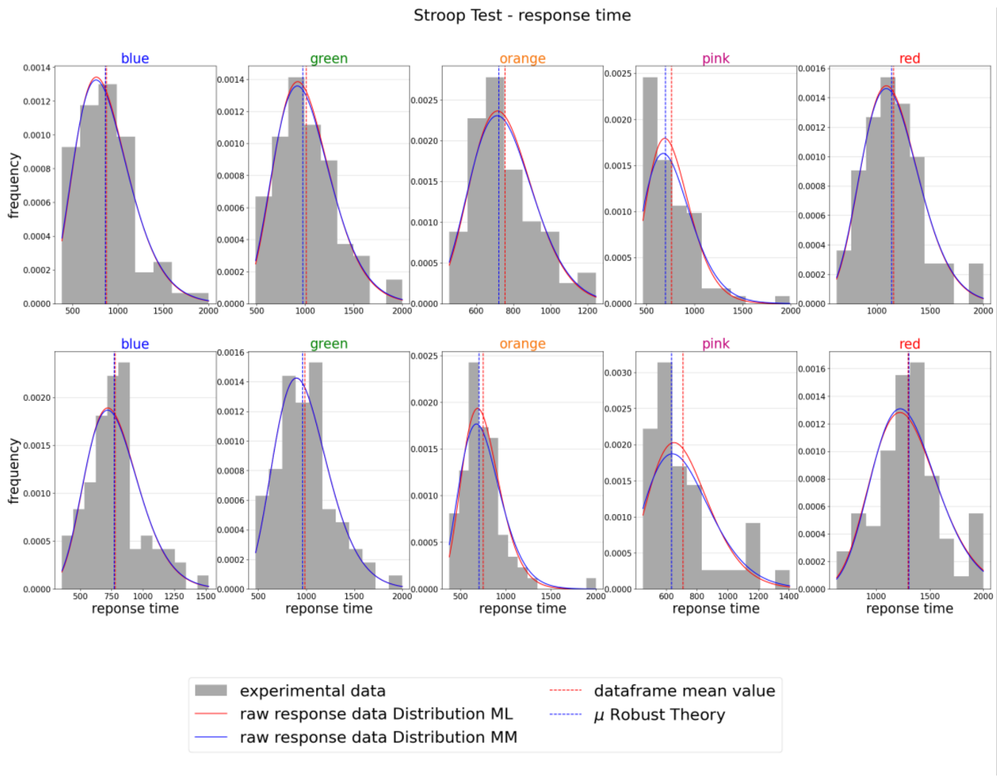

Figure 8: The distribution of the reaction time data for the stroop test

Due to the shape of the distributions, two sample t-test alone is used to assess the hypothesis credibility. This data is shown in table 6. Again, the hypothesis is rejected for most of the participants. However, it seems that red participant's reaction time affected under the dehydration condition.

Table 6: P value and stat value of two sample T-test per participant in the stroop test

colour	blue	green	orange	pink	red
t_value_ttest	2.1703	0.5685	0.1074	1.3726	-3.0826
p_value_ttest	0.5079	0.6426	0.7287	0.543	0.0006

Accuracy

Accuracy is supposed to decrease under the dehydration condition. The accuracy is visualised in figure 9 as the number of correct answers. As can be seen, the number of correct answers is similar with all participants. The blue and green participant show an increase in number of correct answers, which is contradictory to the expectation. The orange, pink and red participant show a slight decrease in number of correct answers.

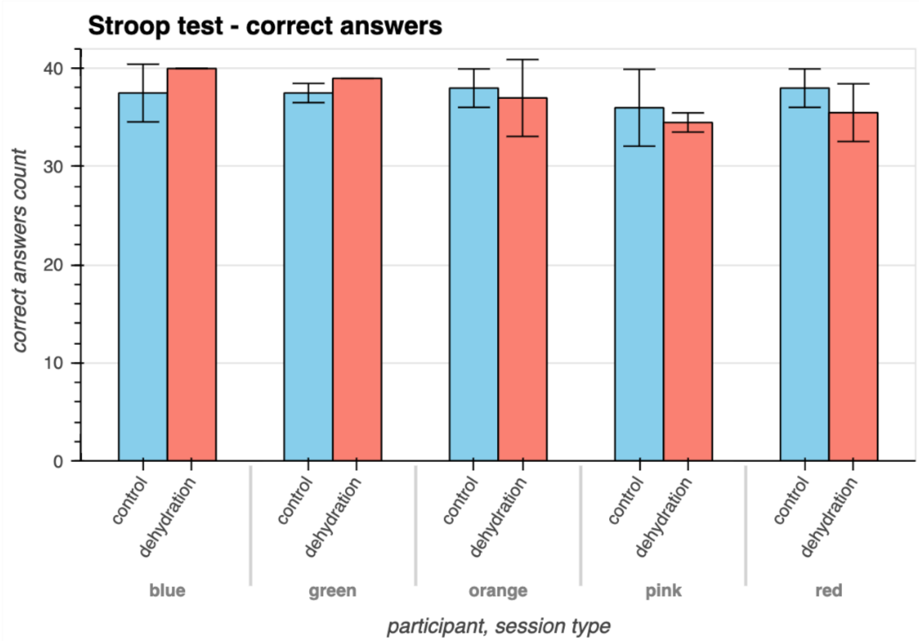

Figure 9: Bar plot of the average of correct answers per participant, per session type in the stroop test

Figure 10 is allocated to present the distribution of the accuracy data. It seems that participant Blue did not make any mistake during the dehydration test.

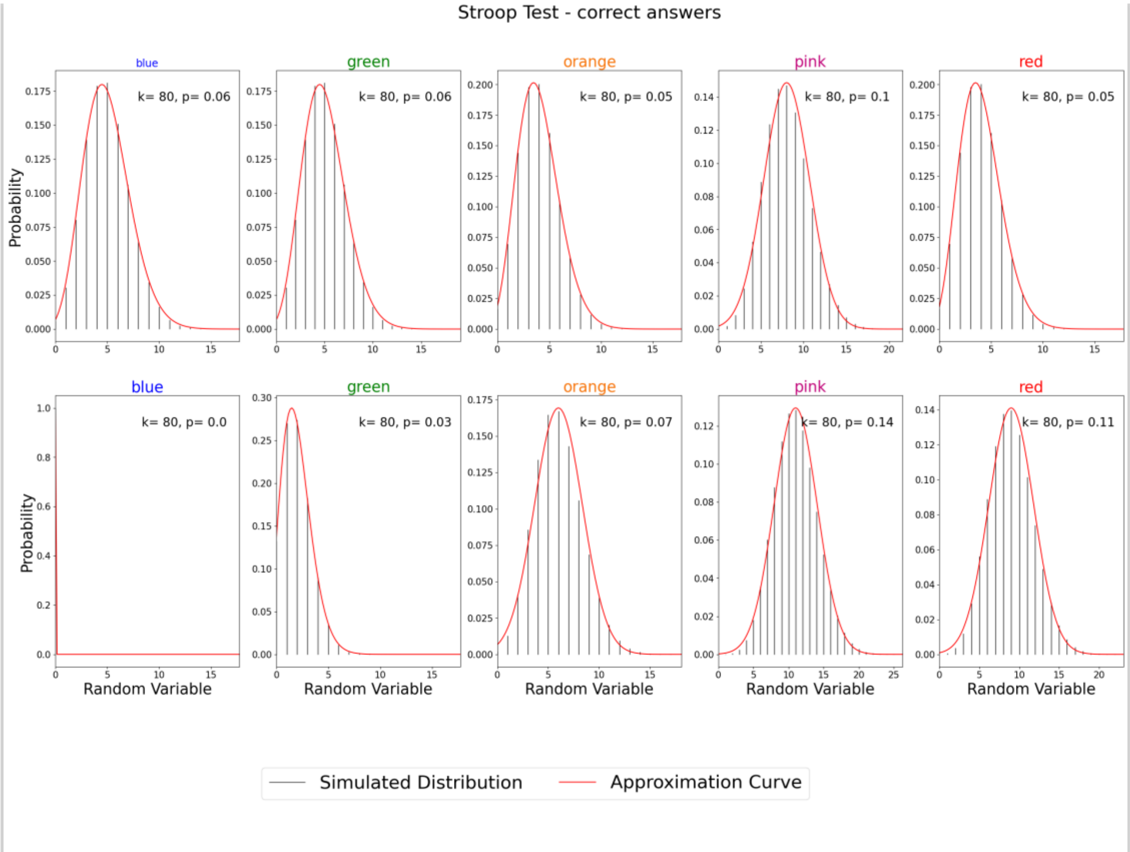

Figure 10:The accuracy distribution per participant in the stroop test

Two sample z-test for proportion results are shown in the table 7. many of the participants did not show significant changes in the number of errors (p value is more than 0.05), so the hypothesis is rejected for them. However, dehydration affected the accuracy of the participant Red. Thus, the hypothesis is approved for the mentioned participant.

Table 7: Z-test parameters per participant of the stroop test

colour	blue	green	orange	pink	red
stat_ztest	2.2718	1.1595	-0.6532	-0.7332	-1.4468
p_value_ztest	0.5058	0.5616	0.1284	0.1159	0.037

Verbal fluency

The verbal fluency tests correspond to the language domain. Here it was expected that the words a person could say is negatively influenced by dehydration. Figure 11 illustrates the average number of words the person reproduced after each session. As expected, the number of words decreased in dehydration session for red and pink (4 words in average). Furthermore, orange and green participants' performance were only slightly negatively affected by losing water and there is a slight difference in their result. The blue participant has the opposite performance, which is contradictory to the hypothesis.

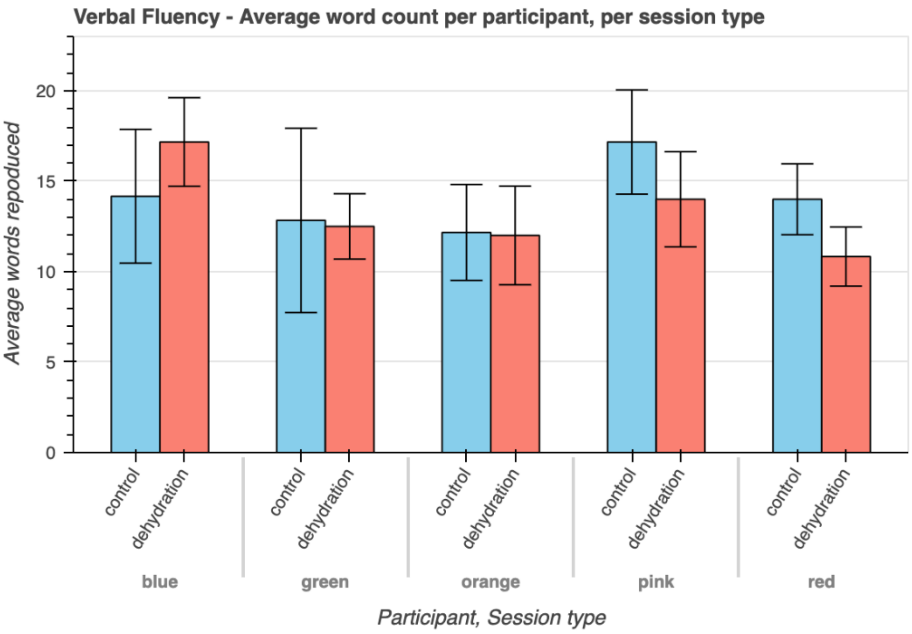

Figure 11: Bar plot of the average word count per participant, per session type in the verbal fluency test

To investigate the hypothesis for each participant a histogram of the number of words per test per participant is sketched Figure 12. Due to the sparse number of data points per data set, the histograms do not show a proper type of distribution.

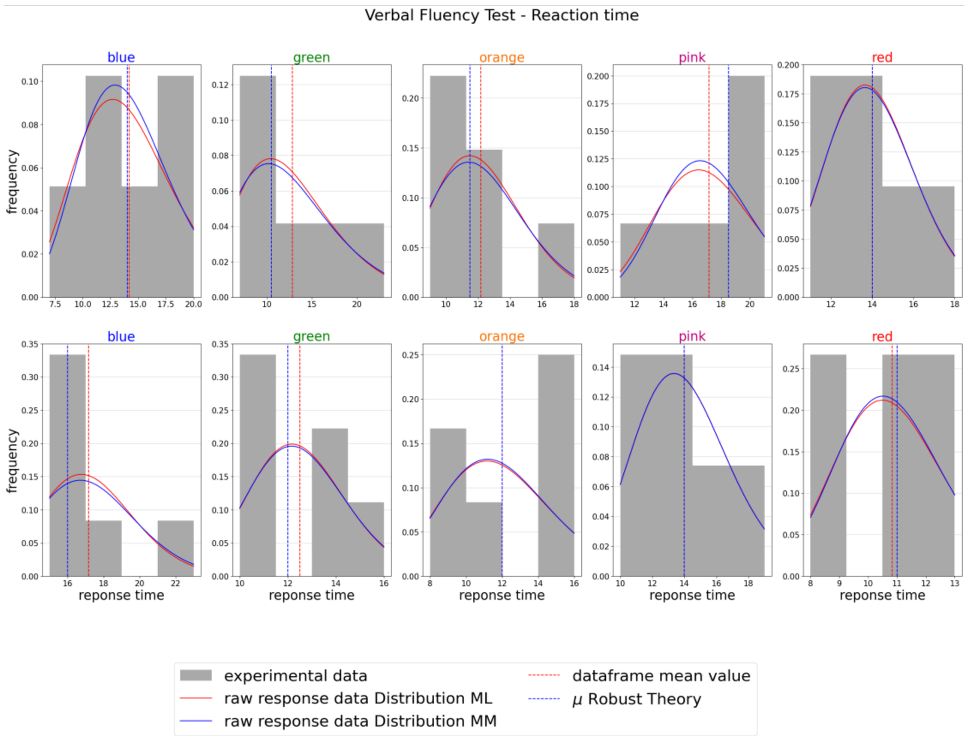

Figure 12: The distribution of the reaction time data of the verbal fluency test

A Q-Q plot is used to see whether the sparse data is distributed normally in Figure 13. It is inferred that most of the data points locate inside 95% confidence intervals (CI).

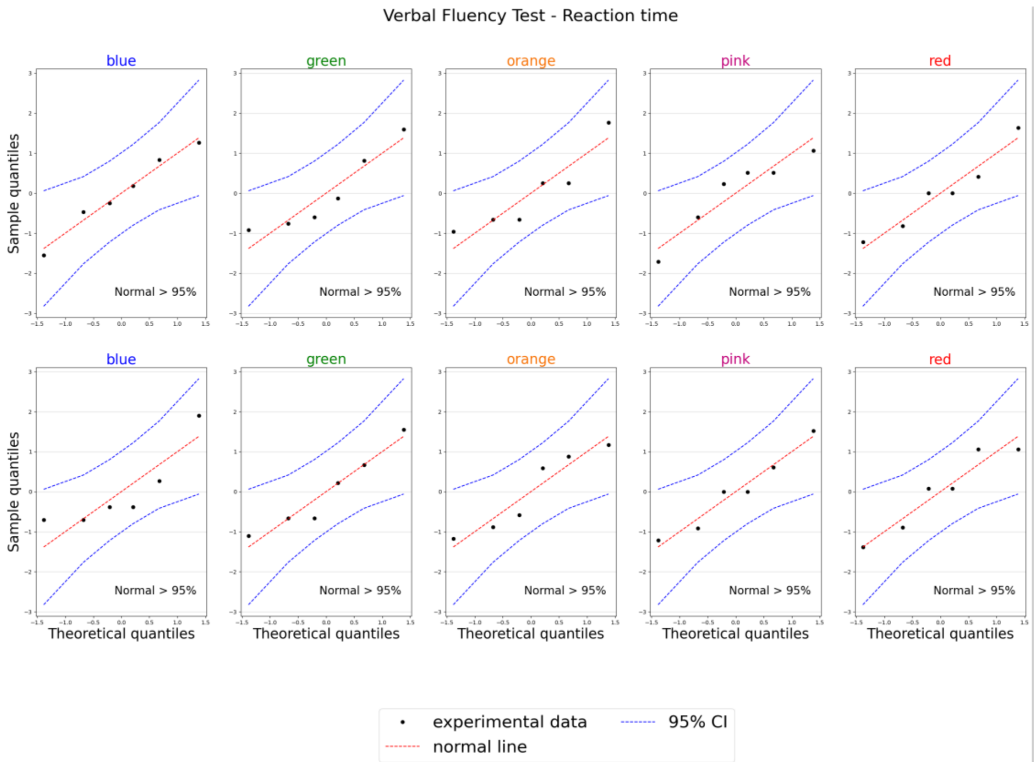

Figure 13: Q-Q plot (Maximum likelihood) per participant of the verbal fluency test

Based on this, the best statistical test that can be utilized in this experiment is 2-sample t-test since the data is normal and there is no information about μ and σ of the dataset Table 8. For all the participants the p value is more than $\alpha = 0.05$, so the hypothesis is rejected. However, due to the lack of data these results cannot be validated.

Table 8: T-test parameters per participant of the verbal fluency test

colour	blue	green	orange	pink	red
t_value_ttest	-1.3255	0.1208	0.0859	1.5911	2.4327
p_value_ttest	0.0547	0.7269	0.7333	0.5357	0.509

Digit span test

Accuracy

The digit span test was used to test the learning and memory domain. In this test the memorized sequence length is expected to decrease after dehydration. This data is visualised in figure 14. All participants performed better or equal in the control sessions than in the dehydration sessions.

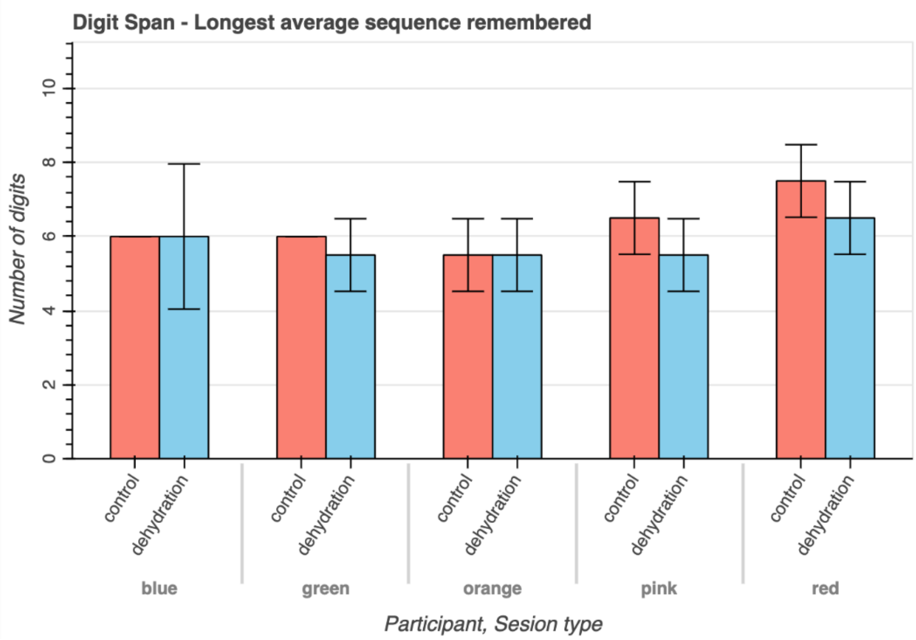

Figure 14: Bar plot of the longest average sequence remembered per participant, per session type in the Digit span test.

The data points per dataset is quite sparse. There are only two data points for each data set. Thus, the statistical distribution cannot be determined by known methods. However, a two sample T-test is used to test the hypothesis. The outcomes of this test are shown in table 9. Even though the hypothesis is rejected for all the participants, this is unreliable due to sparse number of datapoints.

Table 9:T-test parameters per participant, in the digit span test

colour	blue	green	orange	pink	red
t_value_ttest	0.0	1.0	0.0	1.4142	1.4142
p_value_ttest	0.25	0.625	0.25	0.5732	0.5732

Stop Signal test

To test the executive function domain, the stop signal test was utilised. This test can be analysed on two parameters: reaction time and accuracy.

Reaction time

The hypothesis for this parameter was that the reaction time increases when a participant is dehydrated. In the Figure 15 below, only one participant was negatively influenced by dehydration. In other words, all people except red, are not negatively influenced by dehydration.

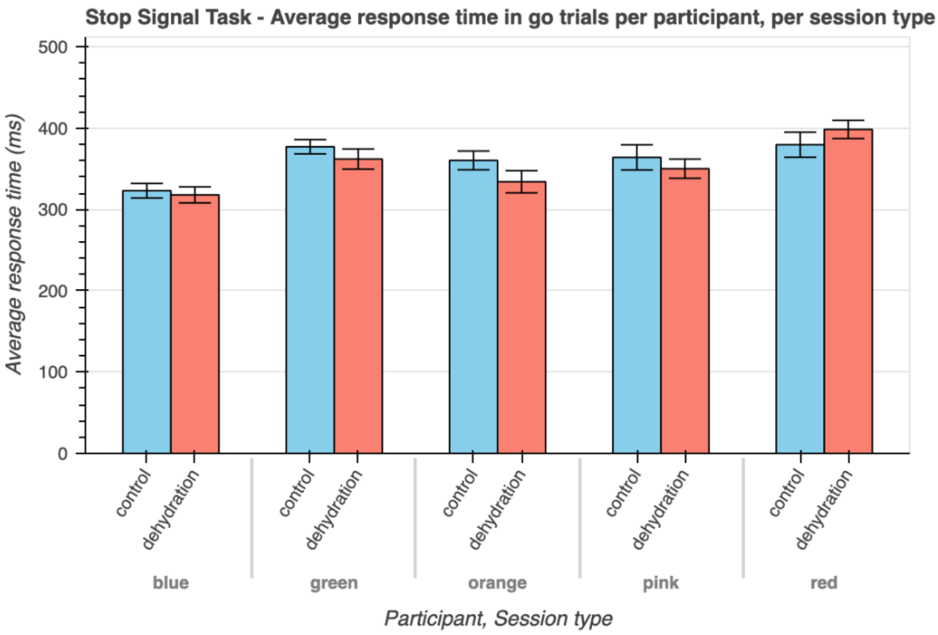

Figure 15: Bar plot of the average response time per participant, per session type in the Stop signal test.

Figure 16 shows the histogram of response time distribution per participant per test. All the distributions follow a Gamma distribution pattern.

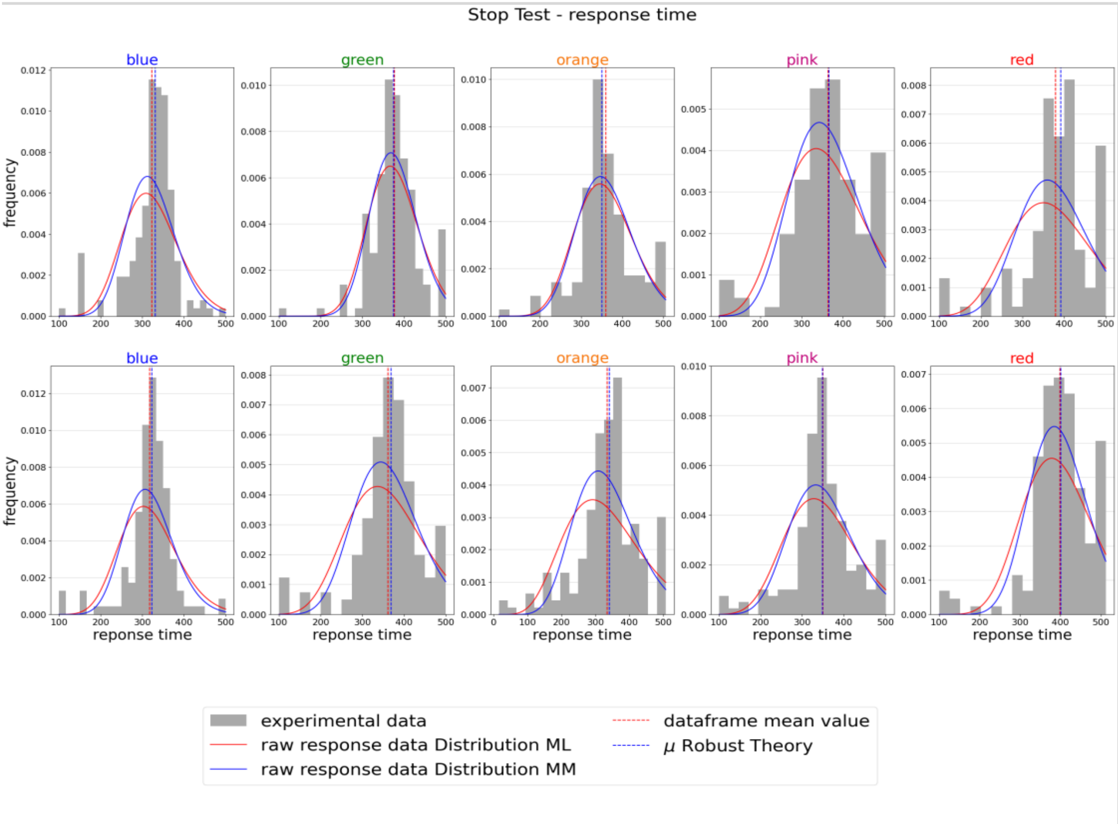

Figure 16: The distribution of the reaction time data in the stop signal test

As it is mentioned in a previous section, 2-sample T-test and Wilcoxon signed-rank test are used for hypothesis validation Table 10. For most of the participants both p values are quite more than $\alpha = 0.05$, so the hypothesis is rejected. However, red showed greater response time after imposing the dehydration condition. Therefore, the hypothesis is approved for this participant.

Table 10: T-test and Wilcoxon test parameters per participant in the stop signal test

colour	blue	green	orange	pink	red
t_value_ttest	1.3263	1.9441	2.9363	1.3618	-2.1801
p_value_ttest	0.5465	0.5132	0.5009	0.5436	0.0076
stat_wilcoxon_test	5525.5	7100.5	6006.0	4408.0	2859.0
p_value_wilcoxon_test	0.5302	0.5209	0.5025	0.5333	0.9944

Accuracy

It is expected that the accuracy decreases in the dehydration condition. Looking at the percentual errors made in the stop signal task, shown in figure 17, we see that this holds true for only two of the participants (orange and pink). Most of the participants actually made fewer errors when dehydrated.

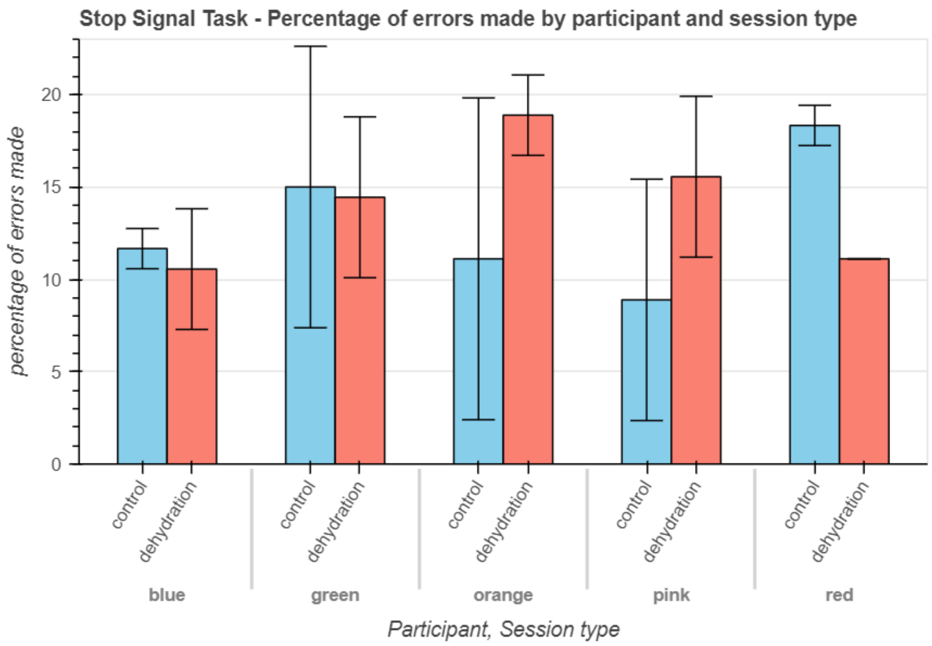

Figure 17:Bar plot of the average errors made participant, per session type in the stop signal test.

The corresponding binomial distributions are sketched in Figure 18. All the distributions can be estimated as normal distributions as shown the mention figure.

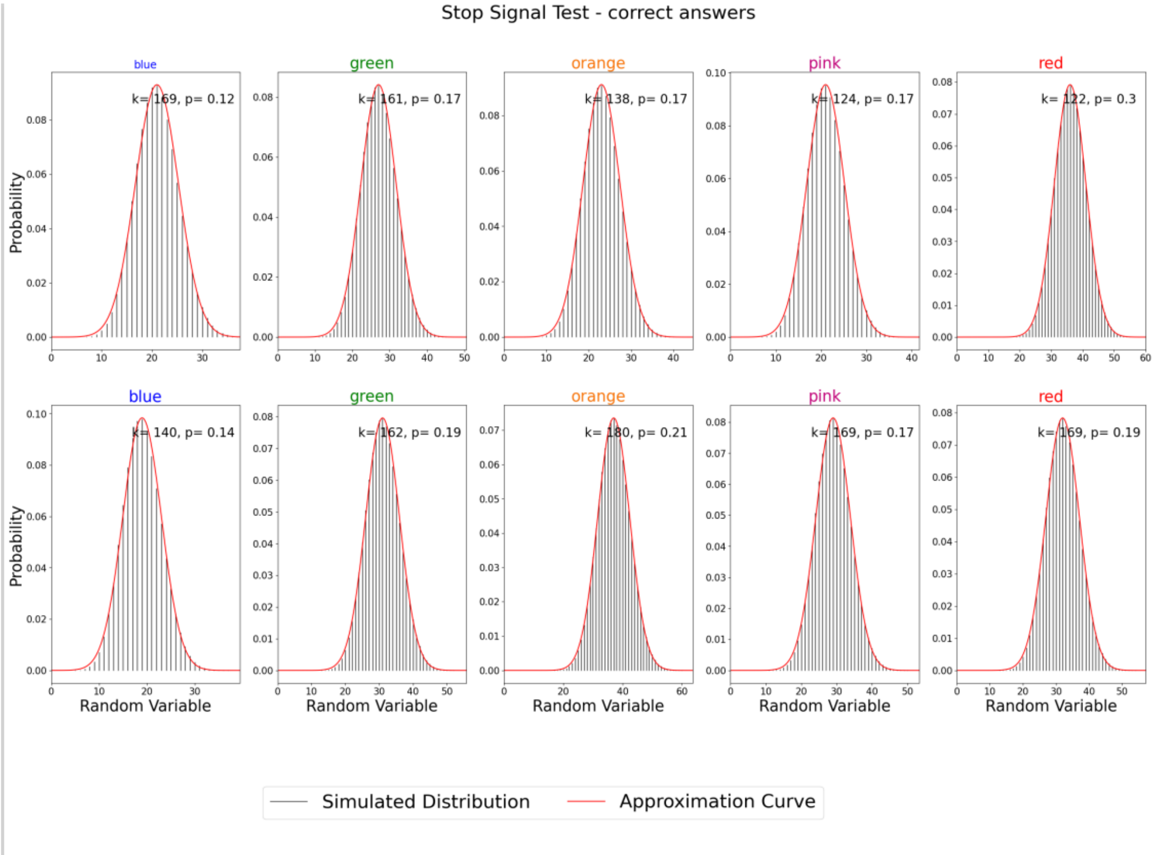

Figure 18: The accuracy distribution per participant in the stop signal test

2-sample z-test for proportions is implemented to evaluate the hypothesis Table 11. For all the participants no significant change in the number of errors is detected per number of tests p, so the hypothesis is rejected for them.

Table 11: Z-test parameters per participant in the stop signal test

colour	blue	green	orange	pink	red
stat_ztest	-0.2986	-0.5538	-0.8785	0.0833	2.1032
p_value_ztest	0.1913	0.1449	0.0949	0.7334	0.5089

Discussion

Although the participants dehydrated themselves, we could not see any significant difference in the performance of the cognitive tests when dehydrated or not. There are a few factors that could have caused a trend to become invisible. For instance, there was no consistent rehydration in the control sessions nor consistent dehydration in the dehydration sessions. Another limitation of this study is the low number of repeats performed per participant. Due to time constraints, the participants only did two repeats. This affected the reliability of the statistical conclusions.

During the control and dehydration sessions the heart rate and the temperature were measured every 5 minutes to ensure the well-being of the participants. While the measured values did not exceed a save level, some of the participants reported feeling unwell while exercising (being dizzy, dazed) in the dehydration sessions and feeling tired, unfocused, and having headaches after the dehydration sessions,

The personal situation of a participant was also not considered. For instance, stress, another factor impacting cognitive functioning (Sandi, 2013), was not accounted for. Furthermore, this research did not control for food intake so a decrease in cognitive functioning could thus also be attributed to a low blood sugar (Graveling et al., 2013).

When looking at the heart rate of the participants we can see that it increased as the exercise session progressed and incremented in intensity. This reflects the fact that the participants made a considerable physical effort in every session, but the weight loss goal was hard to achieve in the 40 min of exercise. In general, the study subjects dehydrated in between 0.66% to 1.23%. Many articles reported a visible and significant effect of dehydration in the cognitive abilities when reaching a minimum of 1.5% to 2% of dehydration (Ganio et al., 2011; Grandjean & Grandjean, 2013).

Sometimes in the control session, participants lost weight, whilst other time they gained weight. Loss of weight is caused by drinking less water than is lost through dehydration during exercise. On the other hand, weigh gain is caused by drinking more water than is lost through dehydration in exercise. Looking back this should be monitored and adjusted before taking the cognitive tests. This could have been achieved by not drinking too much during exercise and measuring the bodyweight right after exercise. The amount of water lost can then be calculated and the participant could drink accordingly. The body then has time absorb this water since there is a recovery period and the participant will be equally hydrated in the control every time. In a future study, this can be incorporated into the experimental design.

In the case of subject blue, there was a body weight gained of 0.28% during a dehydration session. Interestingly, we notice that in all the cognitive tests of this participant, for the sessions reported as dehydrated, the performance was better or equal to the one reported in the control sessions.

Orange was the subject that dehydrated the most from all the participants. We notice that in this state, their performance in 4 of the 5 cognitive tests was equal to or worse than the control when hydrated. In the Stroop test however, they made more errors during the control sessions.

Regarding the cognitive tests there are two possible problems. Firstly, the sensitivity of the tests is not determined in this study. While all the tests we used are well established cognitive test, it is possible that some or all of them are not sensitive enough to determine the subtle cognitive decline present in a (mildly) dehydrated state. Secondly, it is possible that the participants ‘learned’ how to perform one or all the tests after a few repetitions and thus scored better over time. To prevent this we made a few precautions, namely randomising the order of the tests administered, randomising the tests themselves and alternating the control and dehydration session. Looking at the results, there is not a pattern in the results that indicates that we became better with time.

In the future it will be interesting to try to achieve a higher level of dehydration and check the participants cognitive performance. An option is using a method like a sauna, a control environment, that does not require a lot of physical effort and were the participant could stay a long period of time until the high level of dehydration is achieved. However, the wellbeing of the participants need to be taken in account. Pushing the dehydration limit to much may harm the participant. Additionally, in a future study more repeats are also needed in order to achieve a statistically significant result.

Conclusion

The aim of this study was to investigate the short-term effects that dehydration could have on different cognitive domains. In general, this work shows that achieving a dehydration level of at most 1.2% is not enough to significantly affect your mental abilities, but a low degree dehydration (~0.66%) in combination with exercise could affect your personal wellbeing and make you feel unfocused, confusion, headaches or dizziness. It is true that most of the participants were not affected by the experiment circumstances since all the statistical tests reject alternative hypotheses. Nevertheless, the combination of low-level dehydration and unpleasant feeling impacted the red participant. Most of his hypotheses for every cognitive ability approved. In other words, small sample size, experimental platform, hidden variables such as different rates of metabolism per participant, and the sparse number of test runs can affect the outcome of this research project. However, based on the available experimental results and statistical test outcomes no reliable conclusion can be made about the effect of dehydration on the cognitive abilities.

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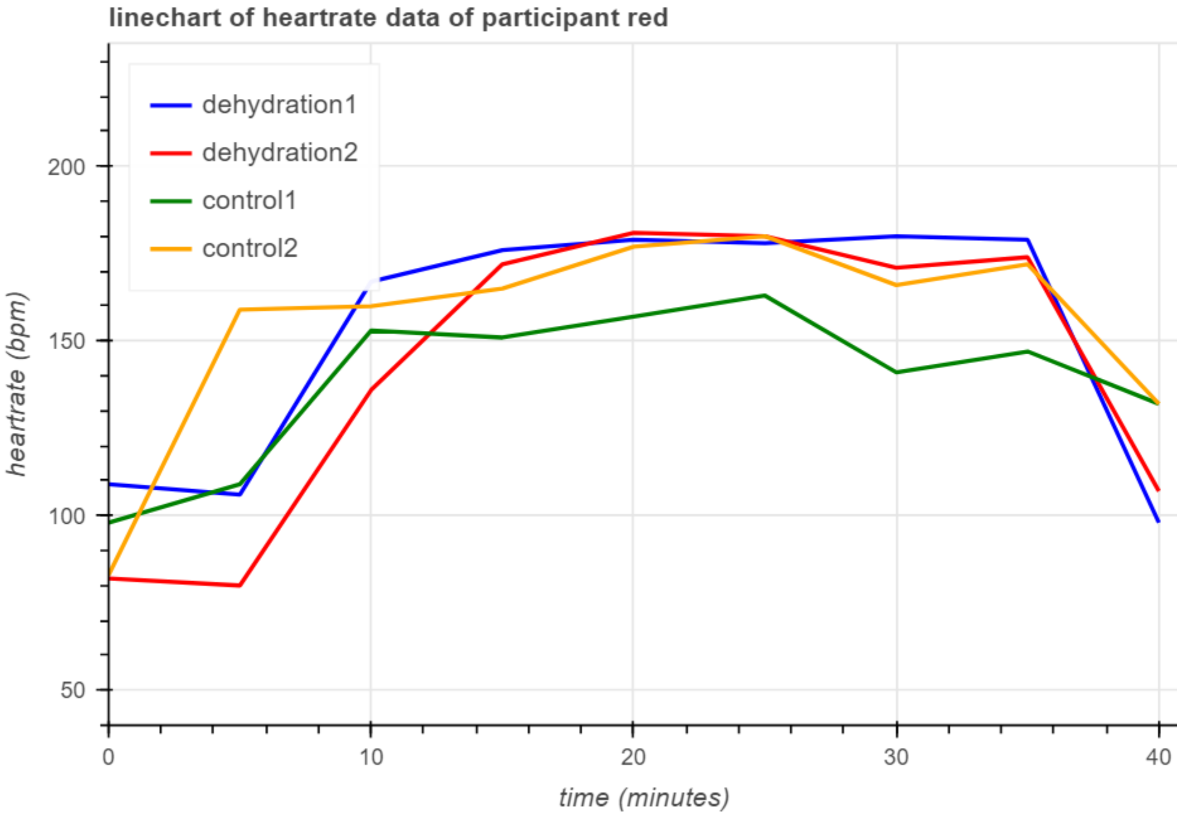
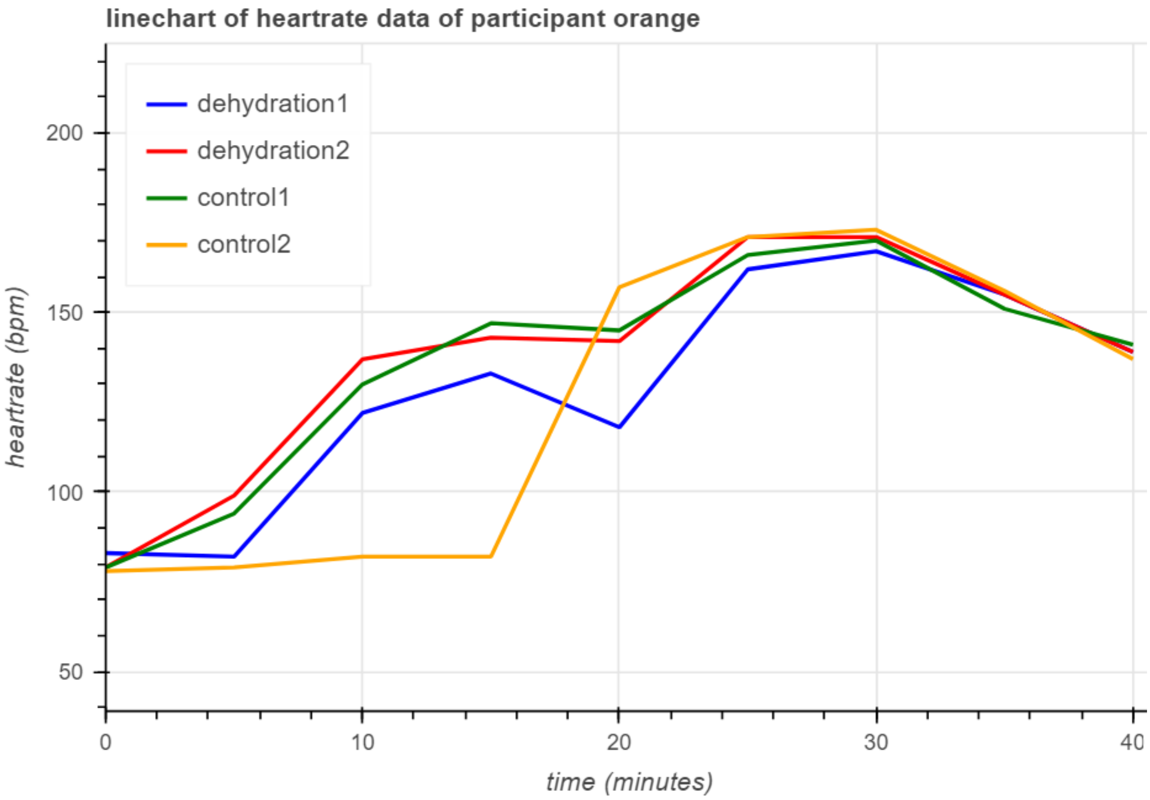
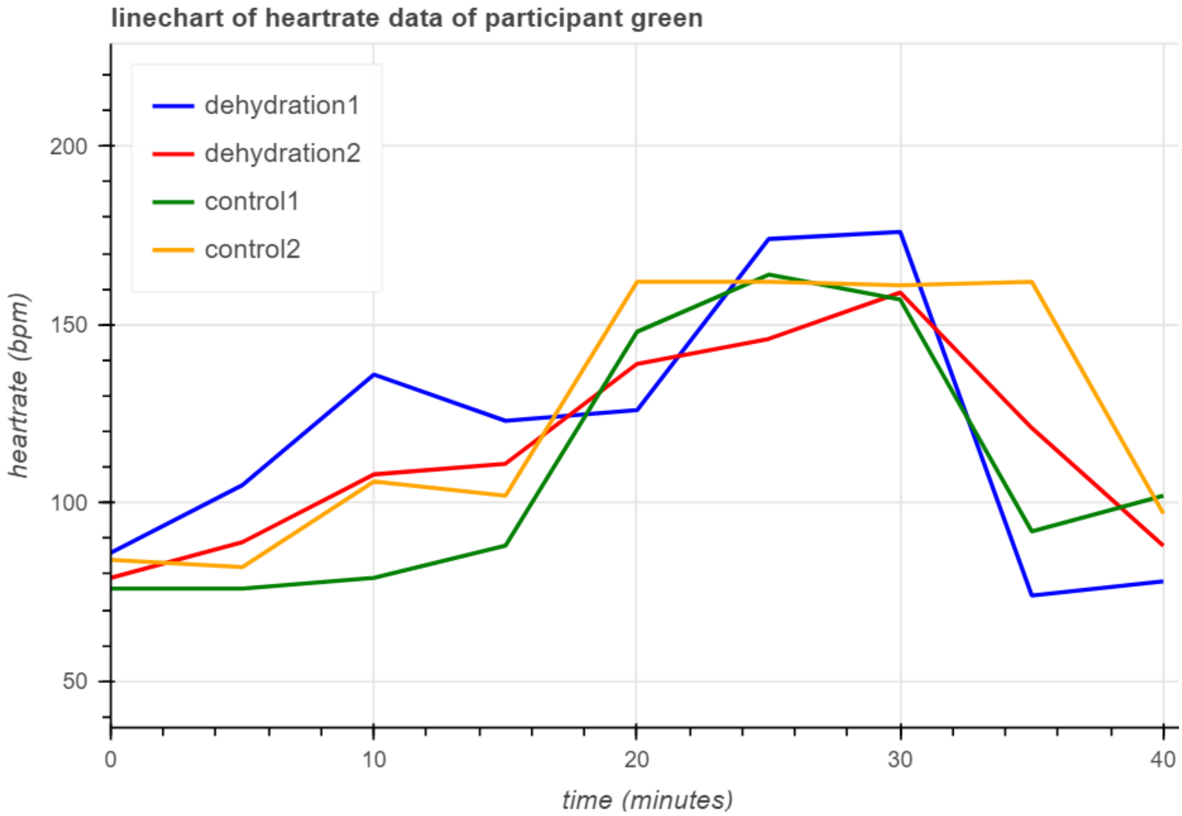
Supplementary material

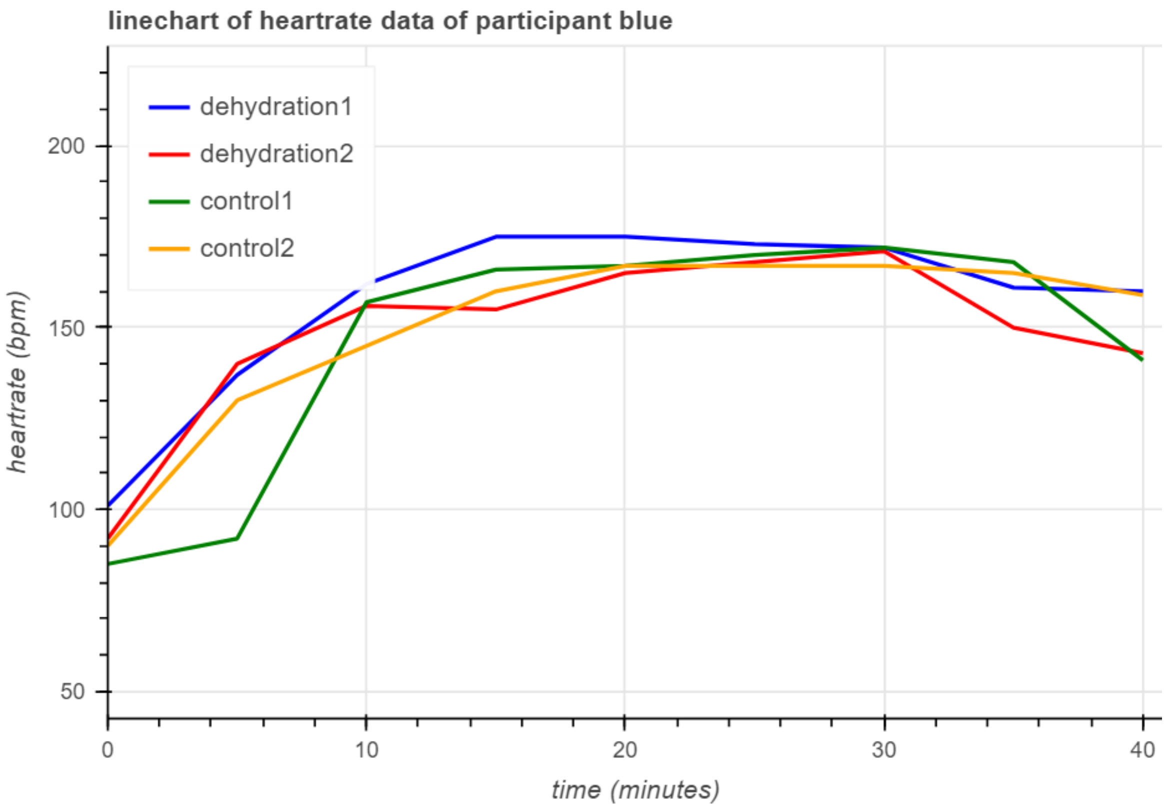
Health data visualisations

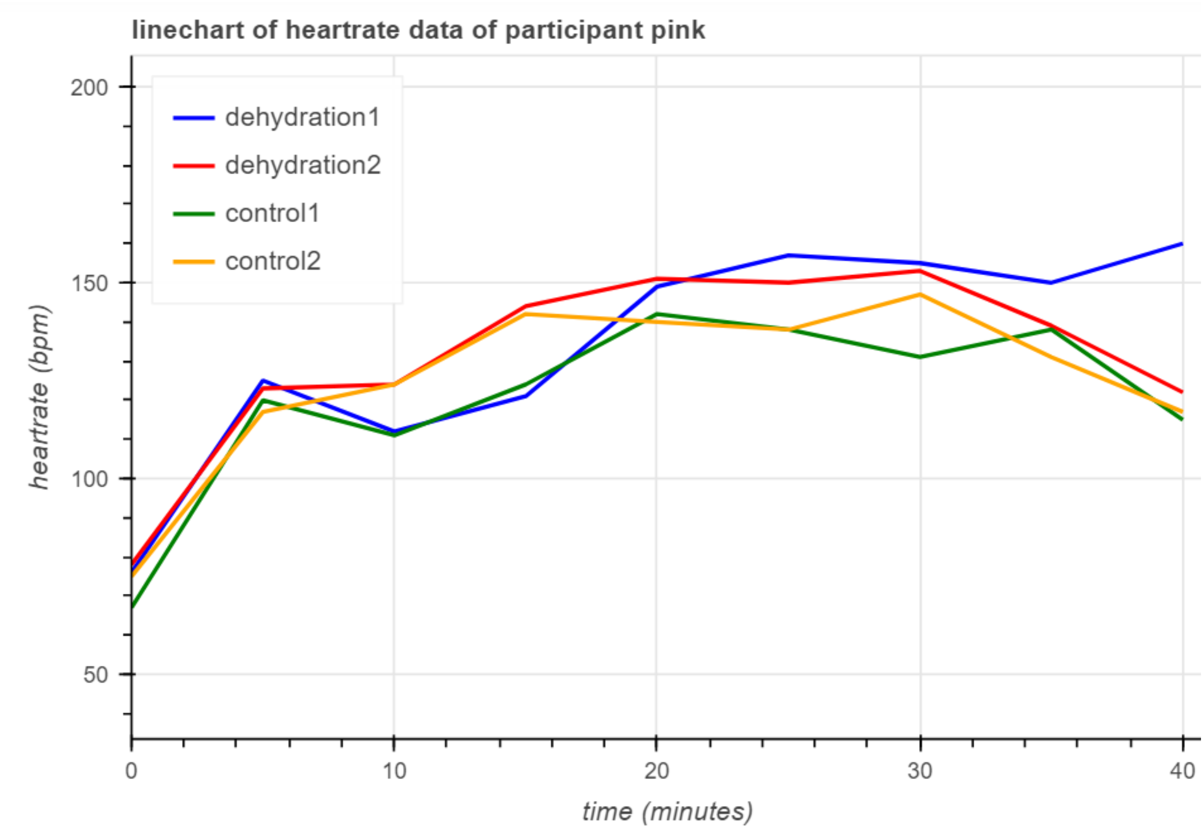
Heartrate



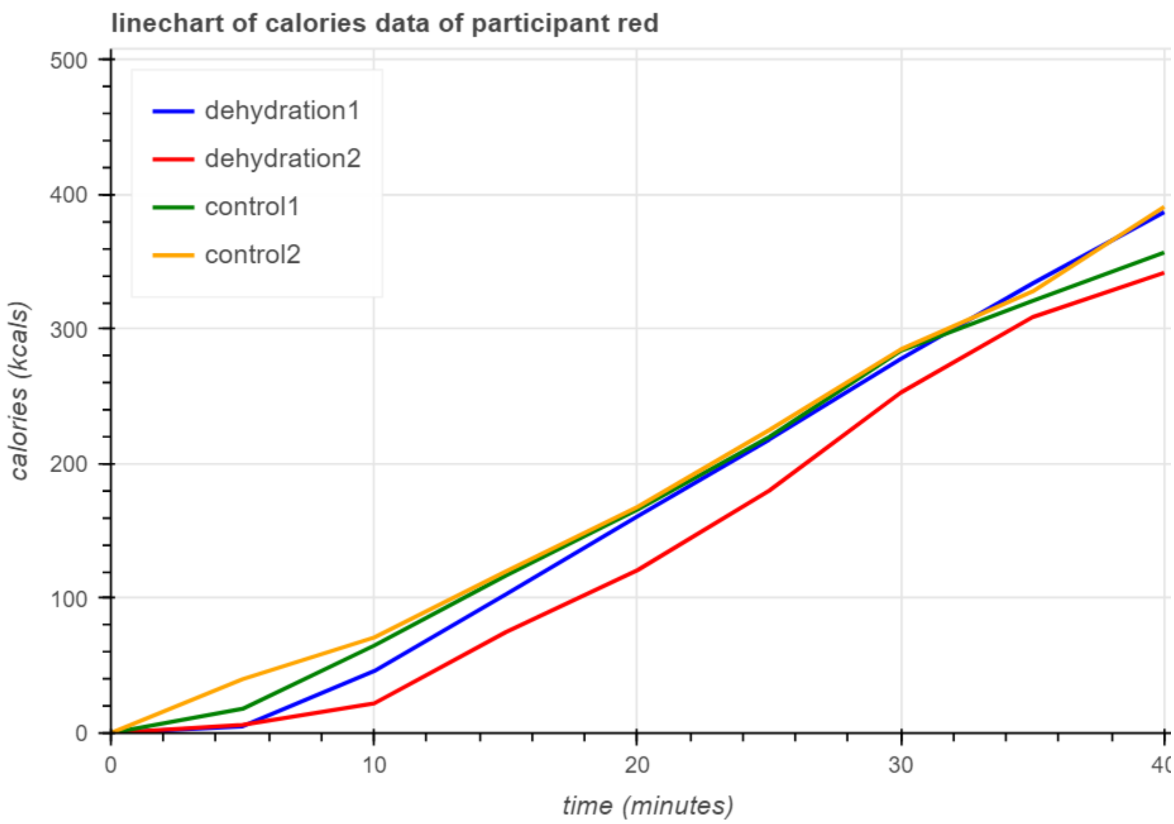


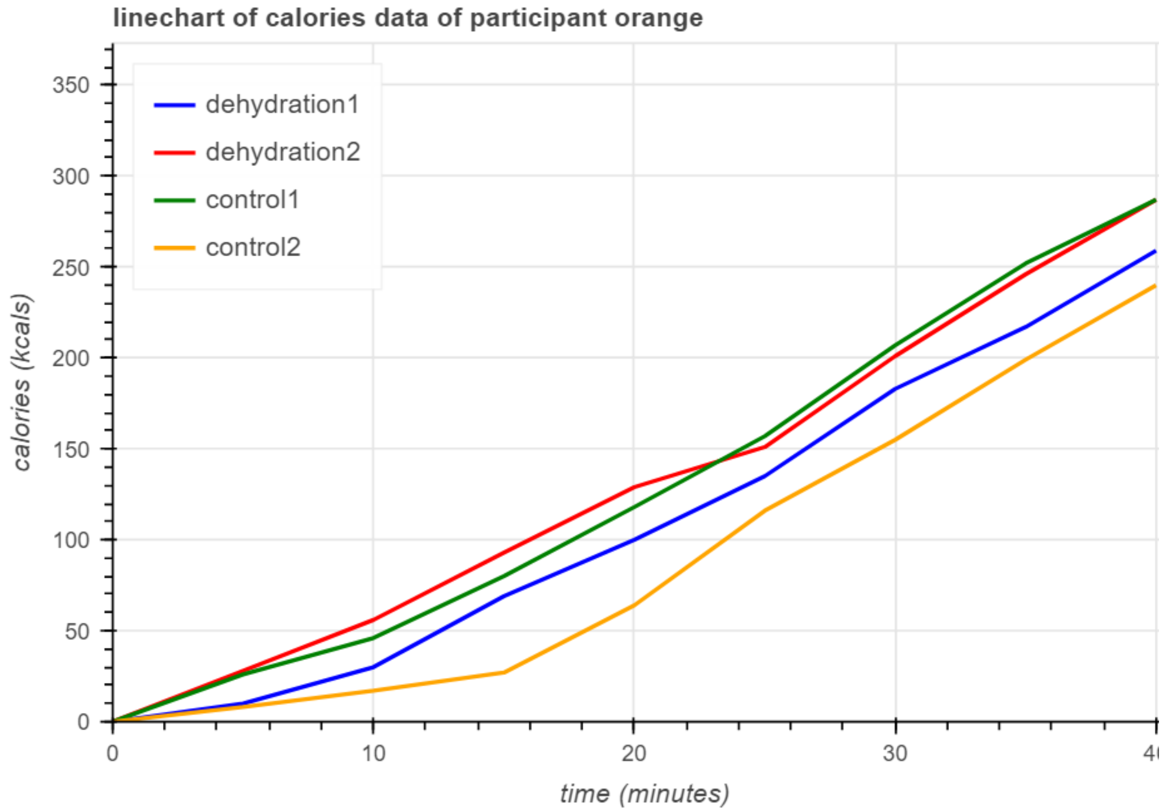

linechart of heartrate data of participant green
dehydration1
dehydration2
control1
control2
heartrate (bpm)
200
150
100
50
0
10
20
30
40
time (minutes)


linechart of heartrate data of participant blue
dehydration1
dehydration2
control1
control2
heartrate (bpm)
200
150
100
50
0
10
20
30
40
time (minutes)



Calories burned

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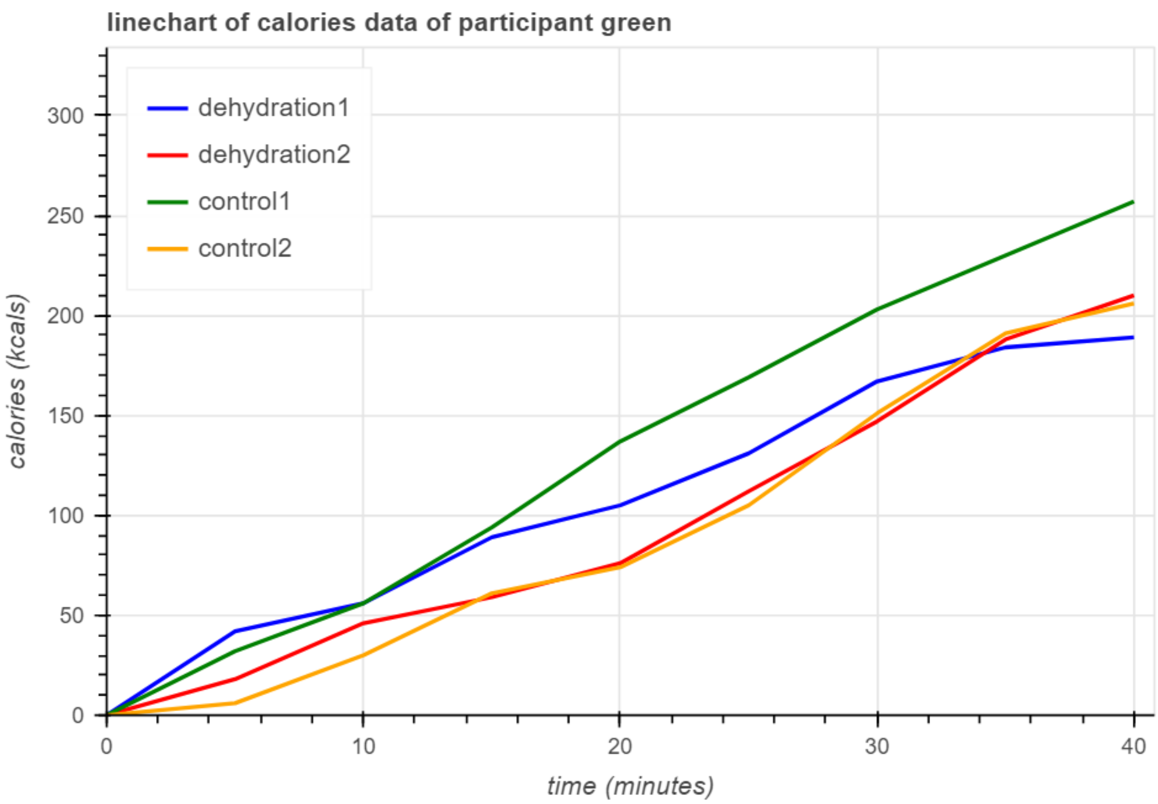
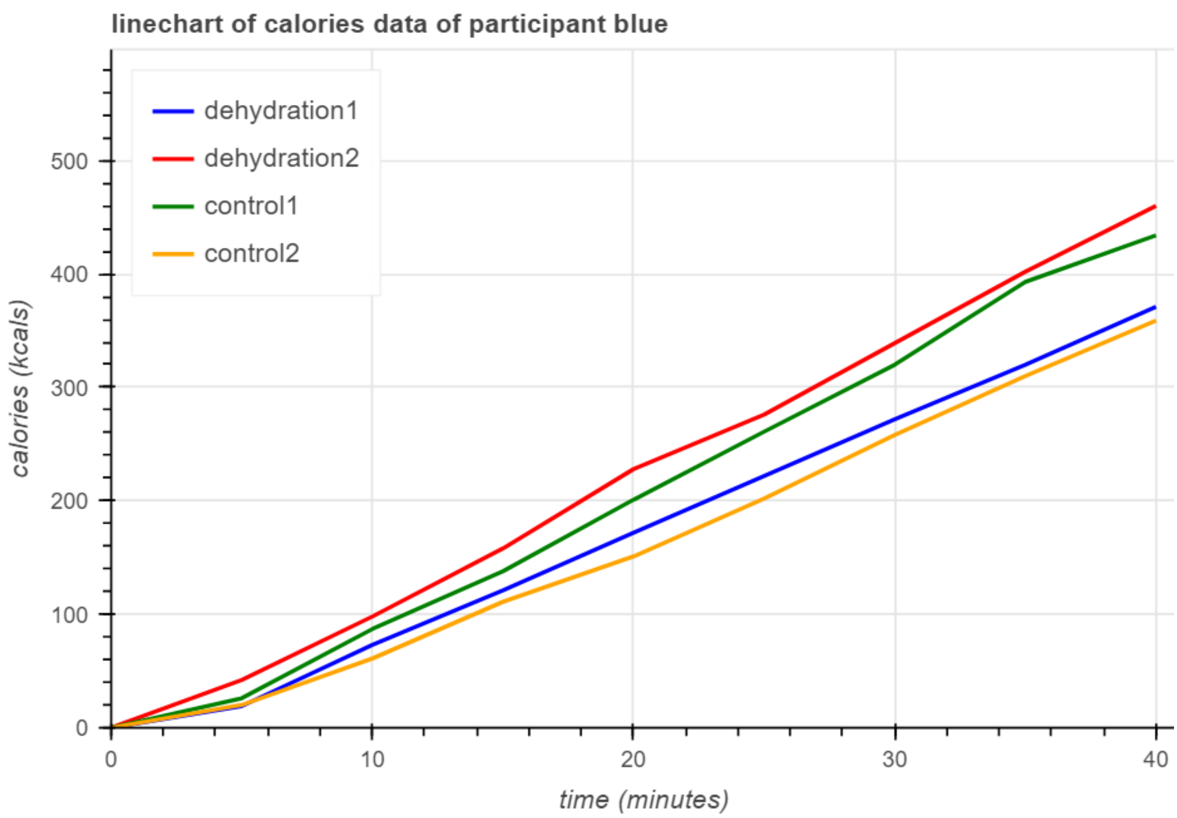
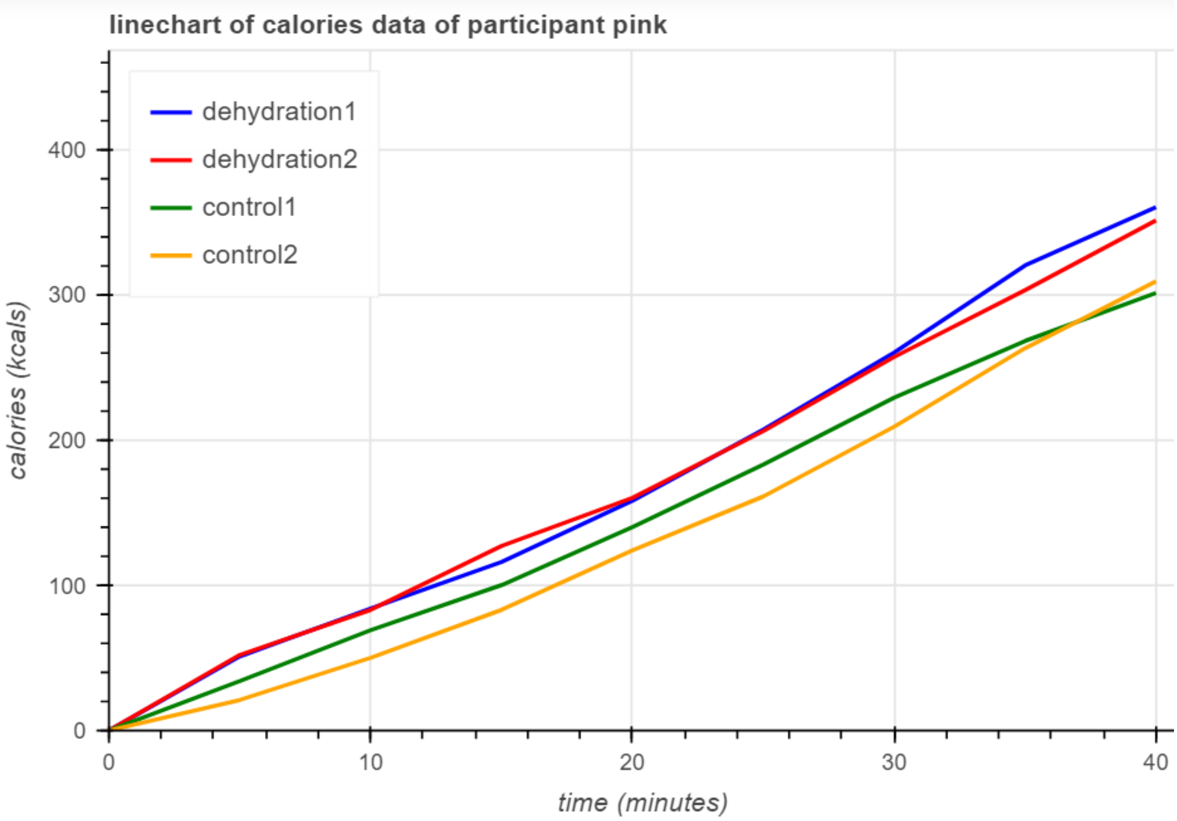
dehydration1
dehydration2
control1
control2
calories (kcals)
350
300
250
200
150
100
50
0
0
10
20
30
40
time (minutes)


linechart of calories data of participant green
dehydration1
dehydration2
control1
control2
calories (kcals)
300
250
200
150
100
50
0
0
10
20
30
40
time (minutes)

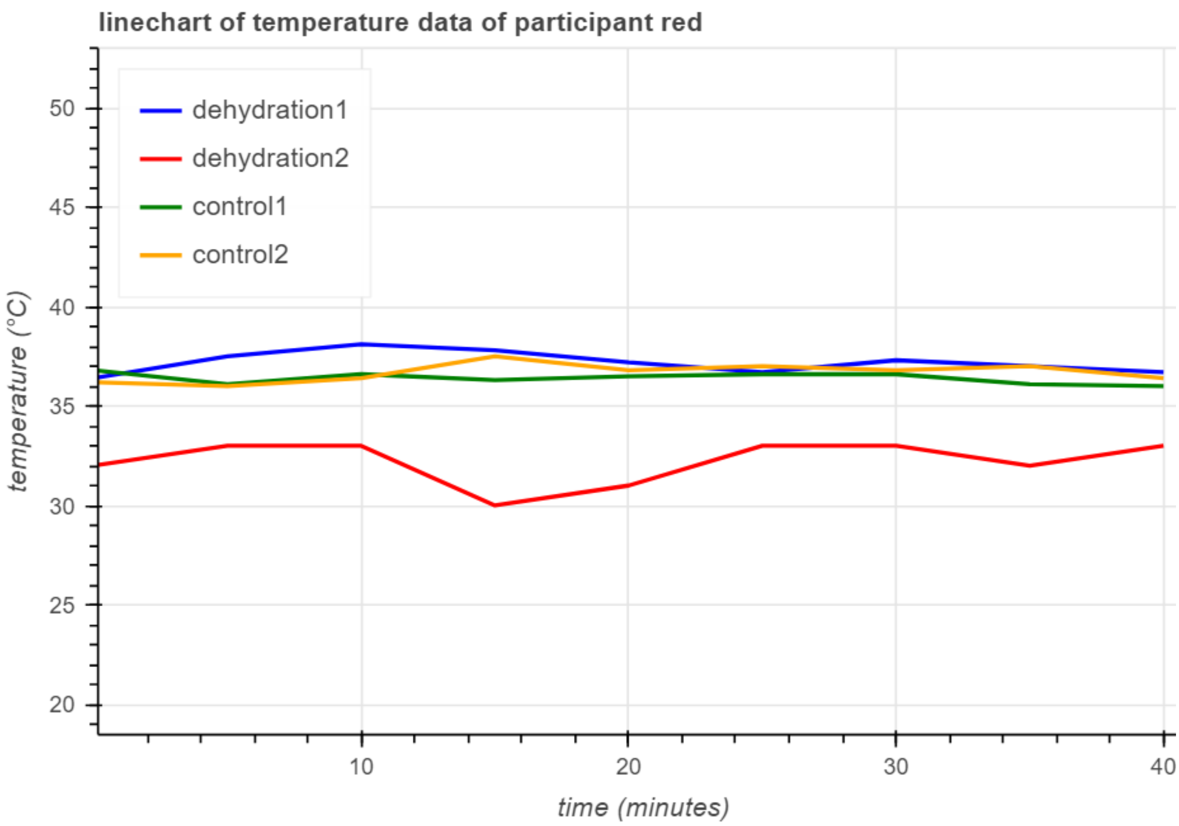


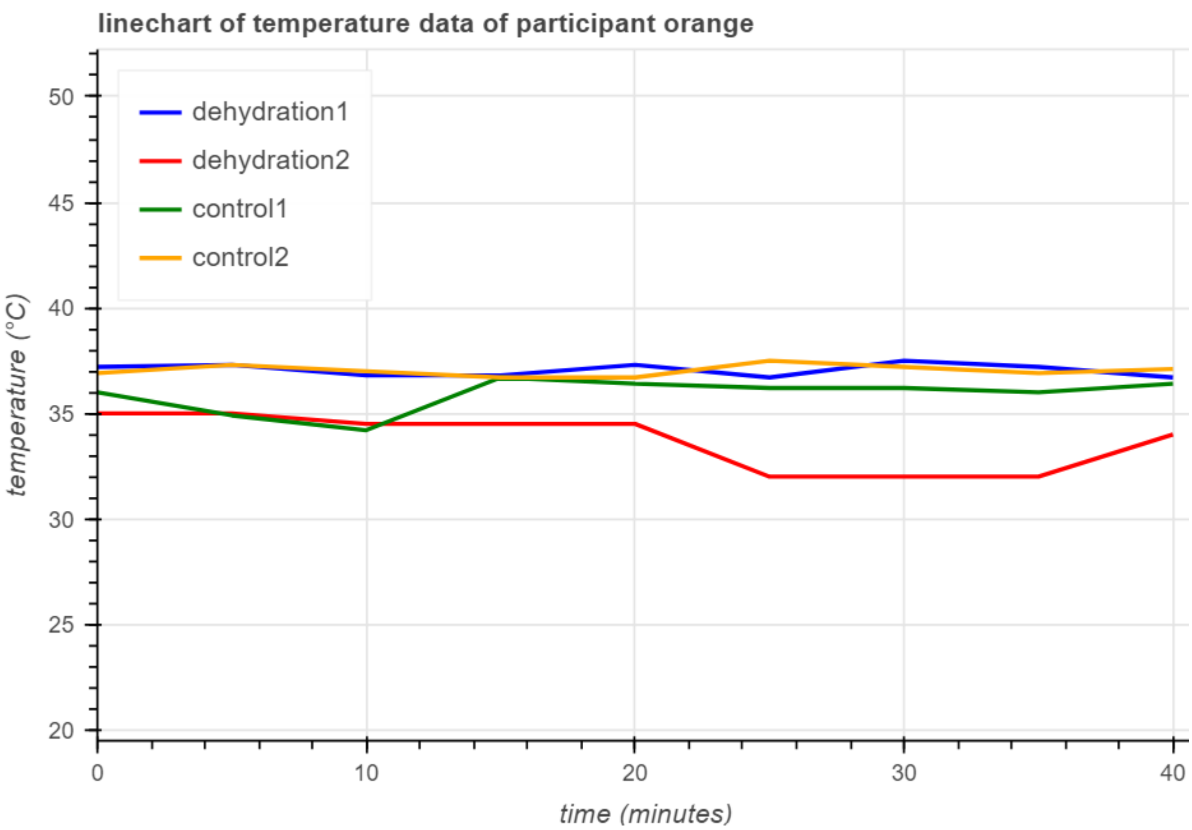
linechart of calories data of participant blue
dehydration1
dehydration2
control1
control2
calories (kcals)
time (minutes)
0
100
200
300
400
500
10
20
30
40

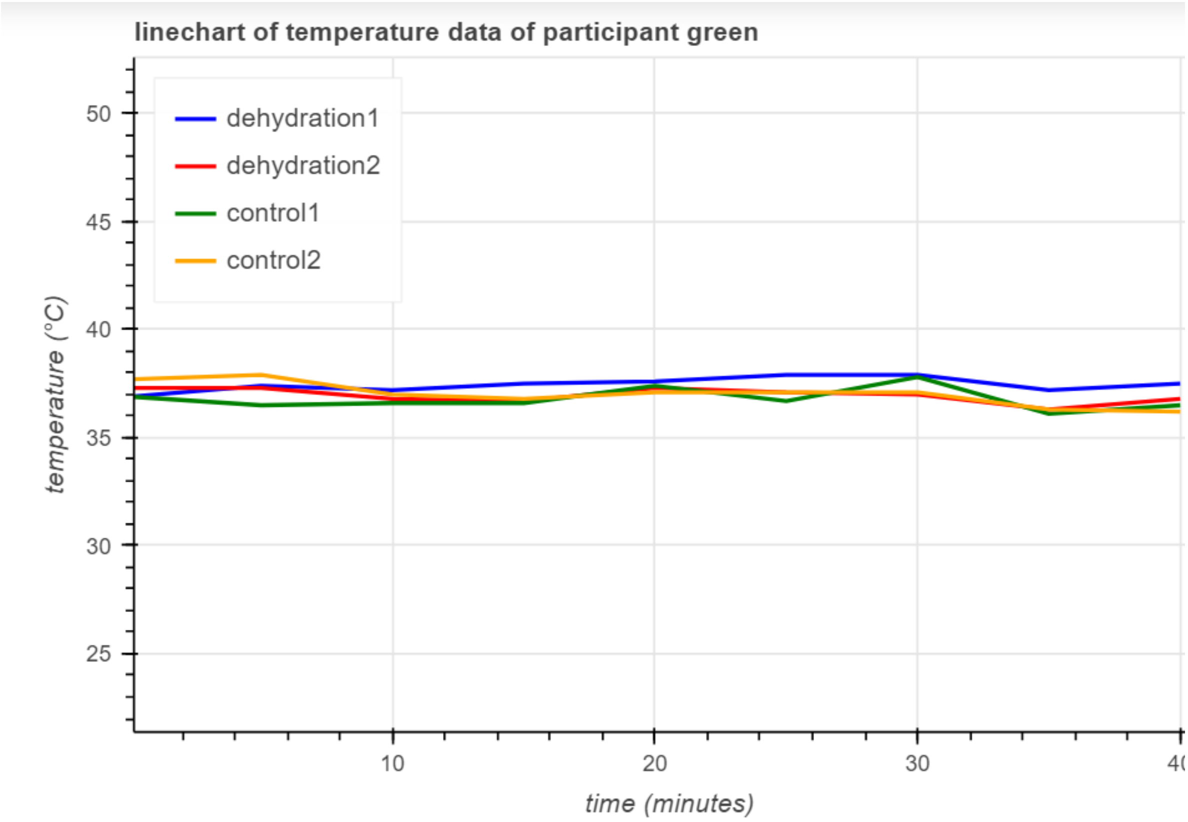


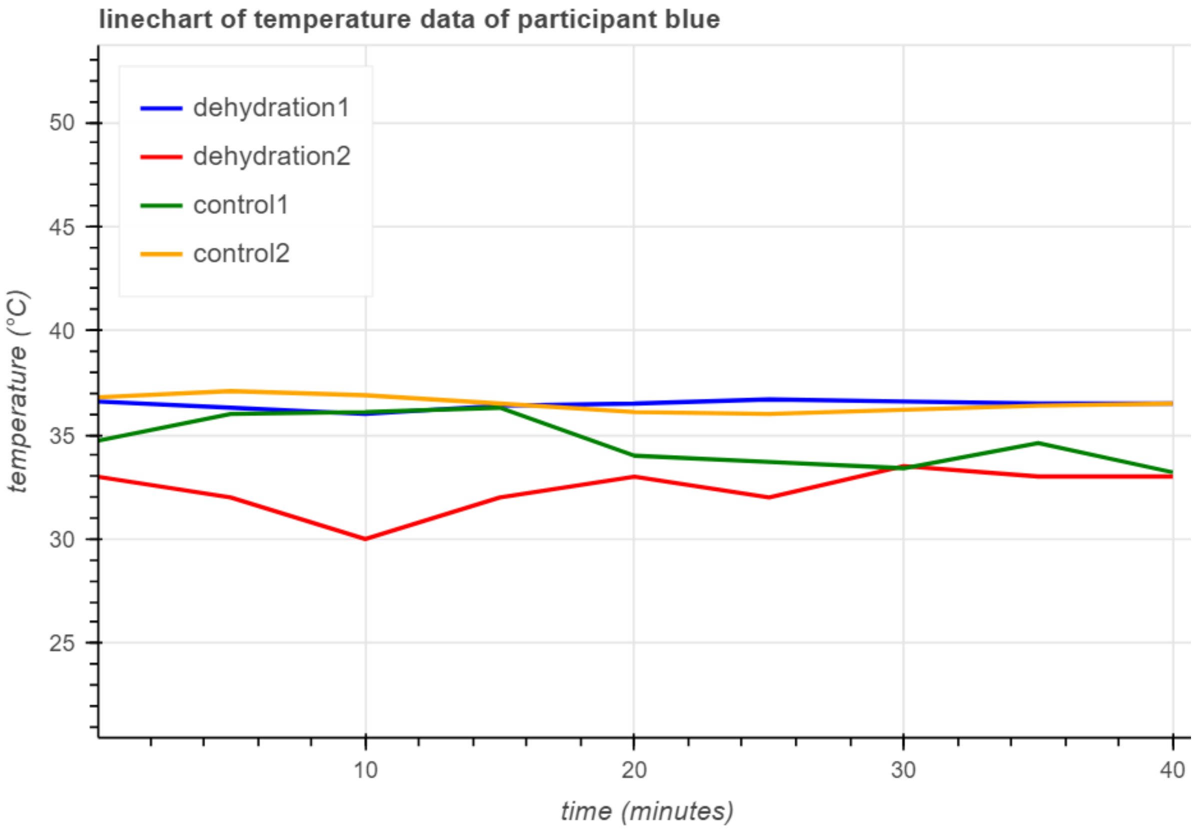
linechart of calories data of participant pink
dehydration1
dehydration2
control1
control2
calories (kcals)
time (minutes)
0
100
200
300
400
10
20
30
40

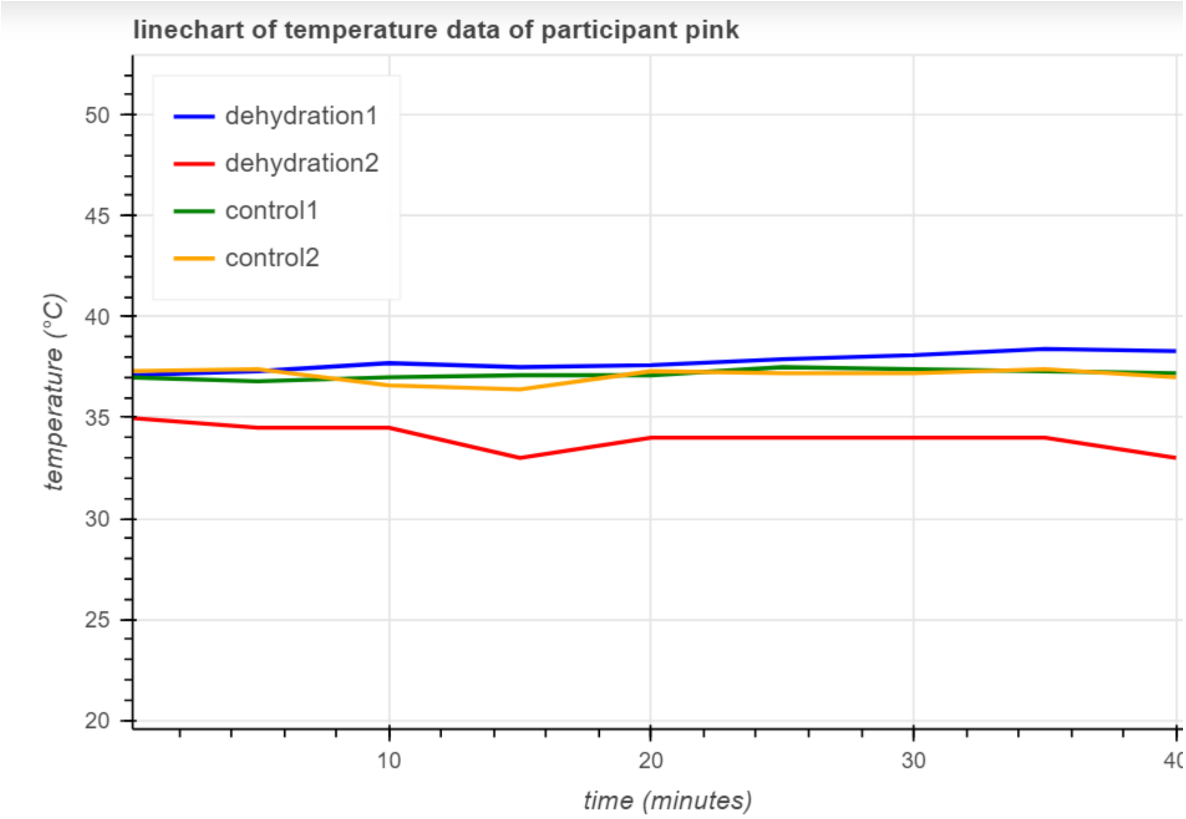
Temperature






linechart of temperature data of participant green
dehydration1
dehydration2
control1
control2
temperature (°C)
time (minutes)


linechart of temperature data of participant blue
dehydration1
dehydration2
control1
control2
temperature (°C)
time (minutes)


linechart of temperature data of participant pink
dehydration1
dehydration2
control1
control2
temperature (°C)
50
45
40
35
30
25
20
10
20
30
40
time (minutes)