OptiVisT questionnaire analysis

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Setup

Import all necessary packages.

```
library(dplyr)
library(tidyverse)
library(ggplot2)
library(psych)
library(corrr)
library(ggcorrplot)
library(FactoMineR)
```

Load the data.

```
# Set working directory to folder with localization files
SAVE <- paste0(getwd(), "/Plots/")
setwd("/Users/florian/Documents/Studium/NBP/Projects/OptiVisT/FloBox/Experiment/Data/Questionnaire/")
# Read in the data
questionnaire_data <- read.csv("questionnaire.csv")
```

Summary statistics

We get summary stats for each question and plot them in a box plot. Some additional comments: for analysis we would probably rather take the median instead of the mean into account, as the mean as central tendency measure might not capture the data's characteristics, e.g. when there are many 1s and 5s, the mean is 3, thus the answer seems to be neutral. The median in fact does not solve that, but might give a better picture (Sullivan & Artino, 2014). Furthermore, Likert scale (ordinal) data usually cannot be seen as interval data, but parametric tests can be used with sufficient sample size as they have higher power (Norman, 2010; de Winter & Dodou, 2010). However, if mean and median do not differ by much, we get the confirmation that the median captures the data's characteristics as well. In our data, this is the case.

```
# Define a custom summary function that calculates statistics with NA values removed
custom_summary <- function(x) c(mean = mean(x, na.rm = TRUE), sd = sd(x, na.rm = TRUE), median = median

# Use sapply with the custom summary function
summary_stats <- sapply(questionnaire_data[, 2:18], custom_summary)

# Convert the result to a data frame for a cleaner display
summary_df <- as.data.frame(summary_stats)
summary_df
```

```
##        I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.
```

```
## mean                                                    1.6785714
## sd                                                      0.9833266
## median                                                  1.0000000
## min                                                     1.0000000
## max                                                     4.0000000
##        I.felt.secure.during.the.task.
## mean                         4.428571
## sd                           1.033820
## median                       5.000000
## min                          1.000000
## max                          5.000000
##        The.tactile.bracelet.is.comfortable.to.wear.
## mean                                       3.821429
## sd                                         1.188013
## median                                     4.000000
## min                                        2.000000
## max                                        5.000000
##        The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.
## mean                                                            1.6785714
## sd                                                              0.9048663
## median                                                          1.0000000
## min                                                             1.0000000
## max                                                             4.0000000
##        The.vibration.motors.were.positioned.correctly.on.my.arm.
## mean                                                   4.1785714
## sd                                                     0.9833266
## median                                                 4.0000000
## min                                                    2.0000000
## max                                                    5.0000000
##        I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.
## mean                                                                 4.7500000
## sd                                                                   0.5181877
## median                                                               5.0000000
## min                                                                  3.0000000
## max                                                                  5.0000000
##        The.intensity.of.vibration.varied.strongly.
## mean                                     1.4642857
## sd                                       0.8811669
## median                                   1.0000000
## min                                      1.0000000
## max                                      5.0000000
##        I.found.the.vibration.intensity.to.be.consistent.
## mean                                          4.6071429
## sd                                            0.5669467
## median                                        5.0000000
## min                                           3.0000000
## max                                           5.0000000
##        I.could.identify.the.vibration.locations.without.much.effort.
## mean                                                        3.571429
## sd                                                          1.168366
## median                                                      4.000000
## min                                                         1.000000
## max                                                         5.000000
##        It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.
```

```
## mean                                                                              2.357143
## sd                                                                                1.026114
## median                                                                            2.000000
## min                                                                               1.000000
## max                                                                               4.000000
##         The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.
## mean                                                                                   4.392857
## sd                                                                                     1.030616
## median                                                                                 5.000000
## min                                                                                    2.000000
## max                                                                                    5.000000
##         I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.
## mean                                                                           4.500000
## sd                                                                             0.745356
## median                                                                         5.000000
## min                                                                            2.000000
## max                                                                            5.000000
##         Mainly.my.intuition.guided.my.hand.movement.during.the.task.
## mean                                                        2.642857
## sd                                                          1.095928
## median                                                      3.000000
## min                                                         1.000000
## max                                                         5.000000
##         X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.
## mean                                                                       4.1071429
## sd                                                                         0.9940298
## median                                                                     4.0000000
## min                                                                        2.0000000
## max                                                                        5.0000000
##         I.was.able.to.develop.a.spatial.understanding.of.the.shelf.
## mean                                                       4.6428571
## sd                                                         0.6214848
## median                                                     5.0000000
## min                                                        3.0000000
## max                                                        5.0000000
##         I.waited.for.instructions.before.reaching.to.grasp.an.object.
## mean                                                         4.0357143
## sd                                                           0.6372477
## median                                                       4.0000000
## min                                                          3.0000000
## max                                                          5.0000000
##         I.was.anticipating.the.grasping.motion.
## mean                                 3.8571429
## sd                                   0.9315175
## median                               4.0000000
## min                                  2.0000000
## max                                  5.0000000
```

```r
# Further get the 1st and 3rd quartile together with mean, median min, max stats
summary(questionnaire_data[,2:18]) # exclude two last participants, as they are blind Ps
```

```
##  I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.
##  Min.   :1.000
##  1st Qu.:1.000
##  Median :1.000
```

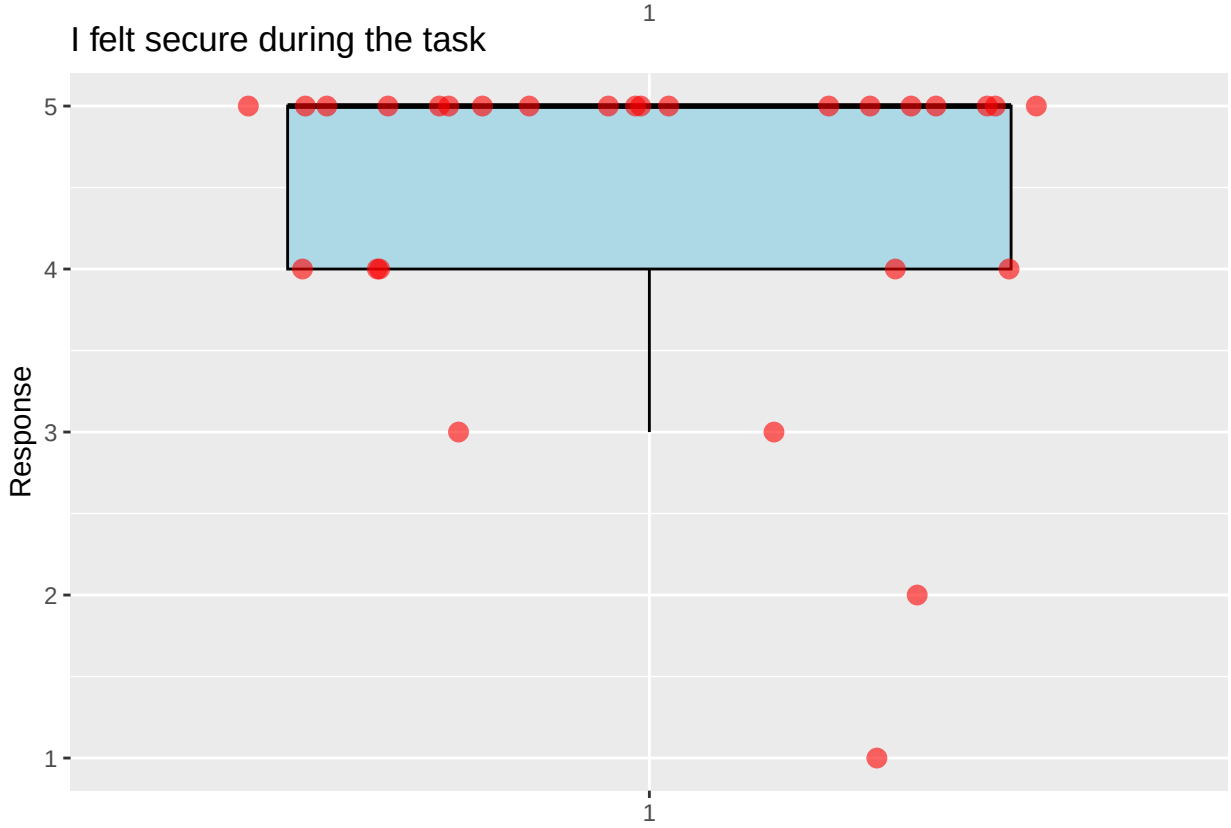
```
##  Mean   :1.679
##  3rd Qu.:2.000
##  Max.   :4.000
##  NA's   :1
##  I.felt.secure.during.the.task. The.tactile.bracelet.is.comfortable.to.wear.
##  Min.   :1.000                  Min.   :2.000
##  1st Qu.:4.000                  1st Qu.:3.000
##  Median :5.000                  Median :4.000
##  Mean   :4.429                  Mean   :3.821
##  3rd Qu.:5.000                  3rd Qu.:5.000
##  Max.   :5.000                  Max.   :5.000
##  NA's   :1                      NA's   :1
##  The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.
##  Min.   :1.000
##  1st Qu.:1.000
##  Median :1.000
##  Mean   :1.679
##  3rd Qu.:2.000
##  Max.   :4.000
##  NA's   :1
##  The.vibration.motors.were.positioned.correctly.on.my.arm.
##  Min.   :2.000
##  1st Qu.:4.000
##  Median :4.000
##  Mean   :4.179
##  3rd Qu.:5.000
##  Max.   :5.000
##  NA's   :1
##  I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.
##  Min.   :3.00
##  1st Qu.:5.00
##  Median :5.00
##  Mean   :4.75
##  3rd Qu.:5.00
##  Max.   :5.00
##  NA's   :1
##  The.intensity.of.vibration.varied.strongly.
##  Min.   :1.000
##  1st Qu.:1.000
##  Median :1.000
##  Mean   :1.464
##  3rd Qu.:2.000
##  Max.   :5.000
##  NA's   :1
##  I.found.the.vibration.intensity.to.be.consistent.
##  Min.   :3.000
##  1st Qu.:4.000
##  Median :5.000
##  Mean   :4.607
##  3rd Qu.:5.000
##  Max.   :5.000
##  NA's   :1
##  I.could.identify.the.vibration.locations.without.much.effort.
##  Min.   :1.000
```

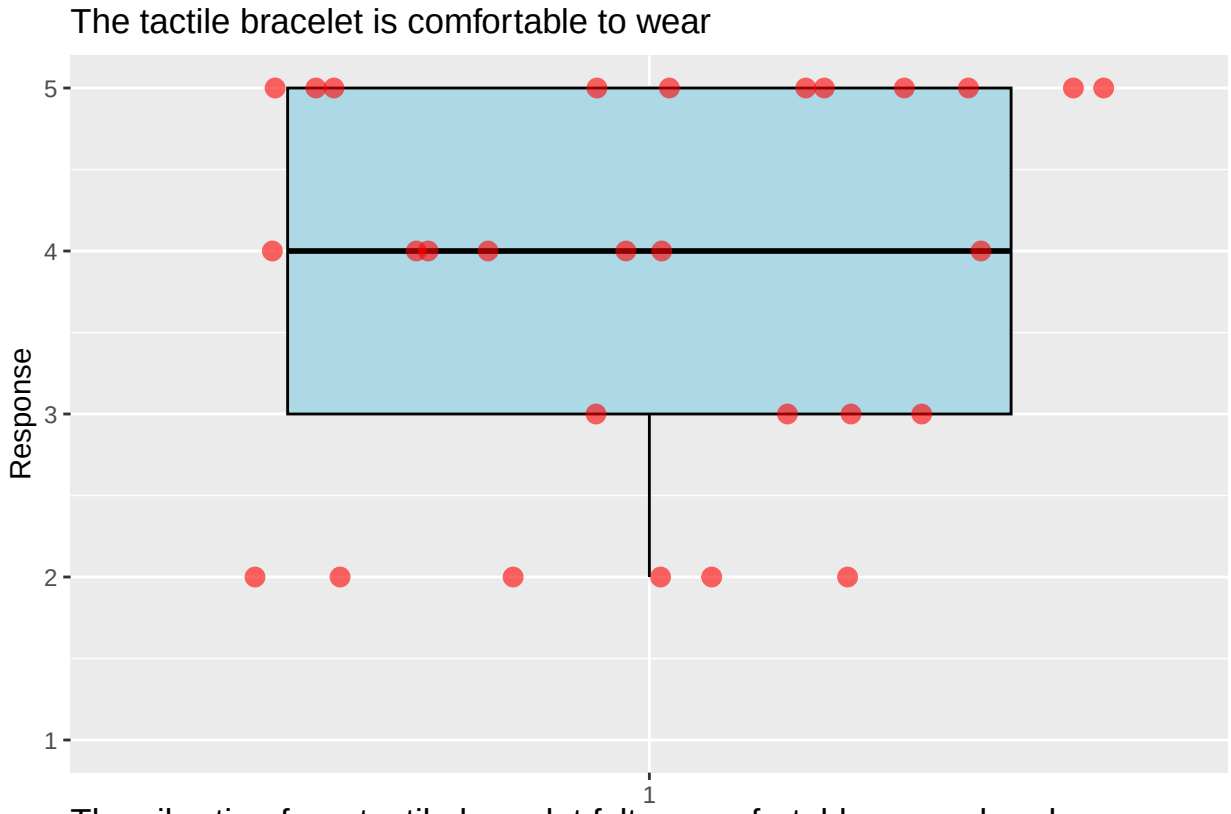
```
##  1st Qu.:3.000
##  Median :4.000
##  Mean   :3.571
##  3rd Qu.:4.250
##  Max.   :5.000
##  NA's   :1
##  It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.
##  Min.   :1.000
##  1st Qu.:2.000
##  Median :2.000
##  Mean   :2.357
##  3rd Qu.:3.000
##  Max.   :4.000
##  NA's   :1
##  The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.
##  Min.   :2.000
##  1st Qu.:4.000
##  Median :5.000
##  Mean   :4.393
##  3rd Qu.:5.000
##  Max.   :5.000
##  NA's   :1
##  I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.
##  Min.   :2.0
##  1st Qu.:4.0
##  Median :5.0
##  Mean   :4.5
##  3rd Qu.:5.0
##  Max.   :5.0
##  NA's   :1
##  Mainly.my.intuition.guided.my.hand.movement.during.the.task.
##  Min.   :1.000
##  1st Qu.:2.000
##  Median :3.000
##  Mean   :2.643
##  3rd Qu.:3.000
##  Max.   :5.000
##  NA's   :1
##  X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.
##  Min.   :2.000
##  1st Qu.:4.000
##  Median :4.000
##  Mean   :4.107
##  3rd Qu.:5.000
##  Max.   :5.000
##  NA's   :1
##  I.was.able.to.develop.a.spatial.understanding.of.the.shelf.
##  Min.   :3.000
##  1st Qu.:4.000
##  Median :5.000
##  Mean   :4.643
##  3rd Qu.:5.000
##  Max.   :5.000
##  NA's   :1
```

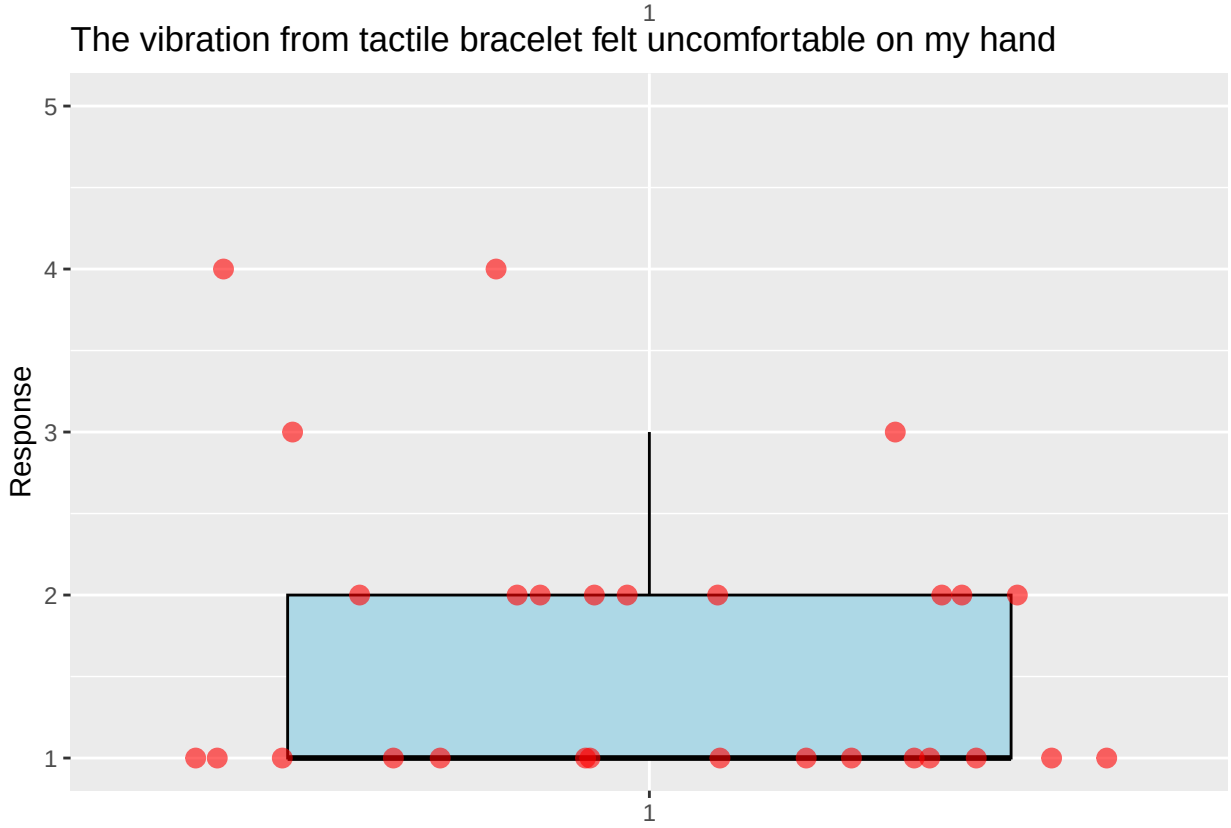
```
##  I.waited.for.instructions.before.reaching.to.grasp.an.object.
##  Min.   :3.000
##  1st Qu.:4.000
##  Median :4.000
##  Mean   :4.036
##  3rd Qu.:4.000
##  Max.   :5.000
##  NA's   :1
##  I.was.anticipating.the.grasping.motion.
##  Min.   :2.000
##  1st Qu.:3.000
##  Median :4.000
##  Mean   :3.857
##  3rd Qu.:5.000
##  Max.   :5.000
##  NA's   :1
```

```r
# Plot each question with box plot
for (col in colnames(questionnaire_data)[2:18]) {
  plot_data <- data.frame(Response = questionnaire_data[, col], Question = gsub("\\.", " ", col))
  plot_title <- gsub("^X", "", col)
  plot_title <- gsub("\\.", " ", plot_title)

  plot <- ggplot(plot_data, aes(x = factor(1), y = Response)) +
    geom_boxplot(fill = "lightblue", color = "black", outlier.shape = NA) +
    geom_jitter(width = 0.5, height = 0, size = 3, alpha = 0.6, color = "red") +  # add points
    labs(title = plot_title, x = "", y = "Response") +
    #theme(axis.text.x = element_blank(), axis.ticks.x = element_blank()) +
    ylim(1, 5)  # set y-axis limits to 1 and 5

  print(plot)
}
```

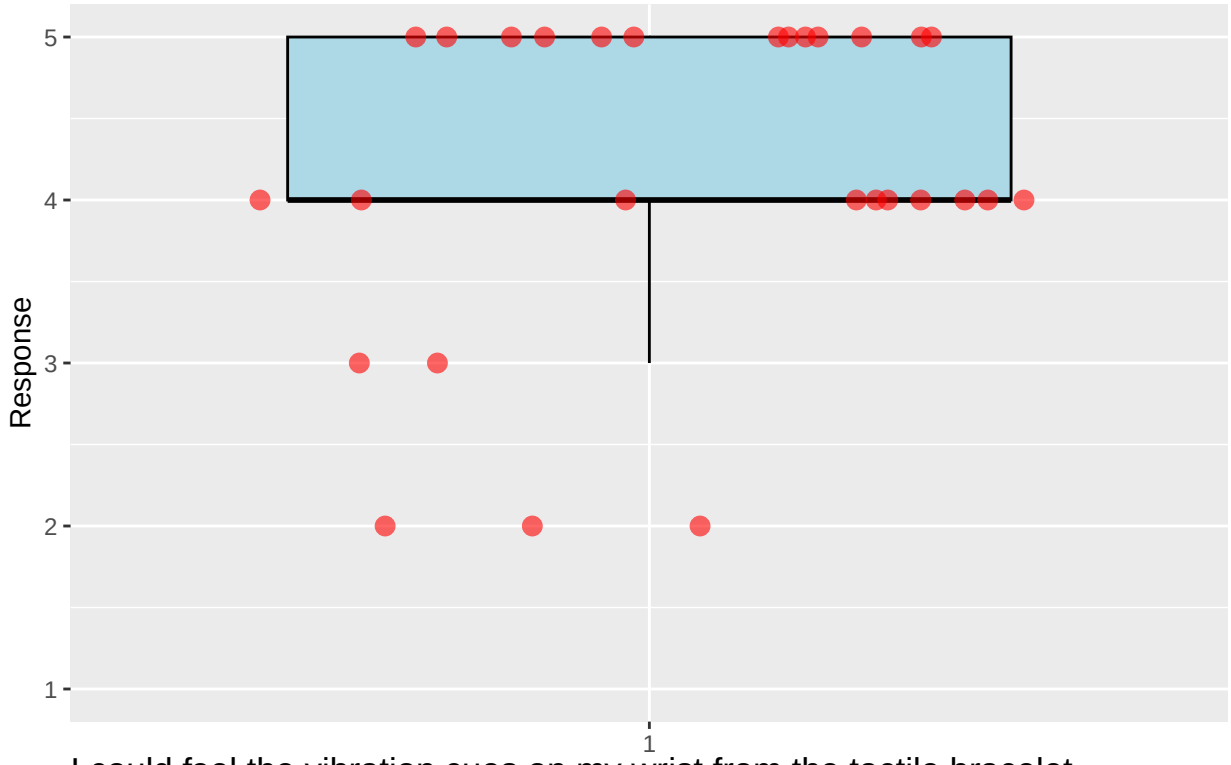

I was in fear of hitting the shelf or objects during the task
Response
5
4
3
2
1
1


I felt secure during the task
Response
5
4
3
2
1
1

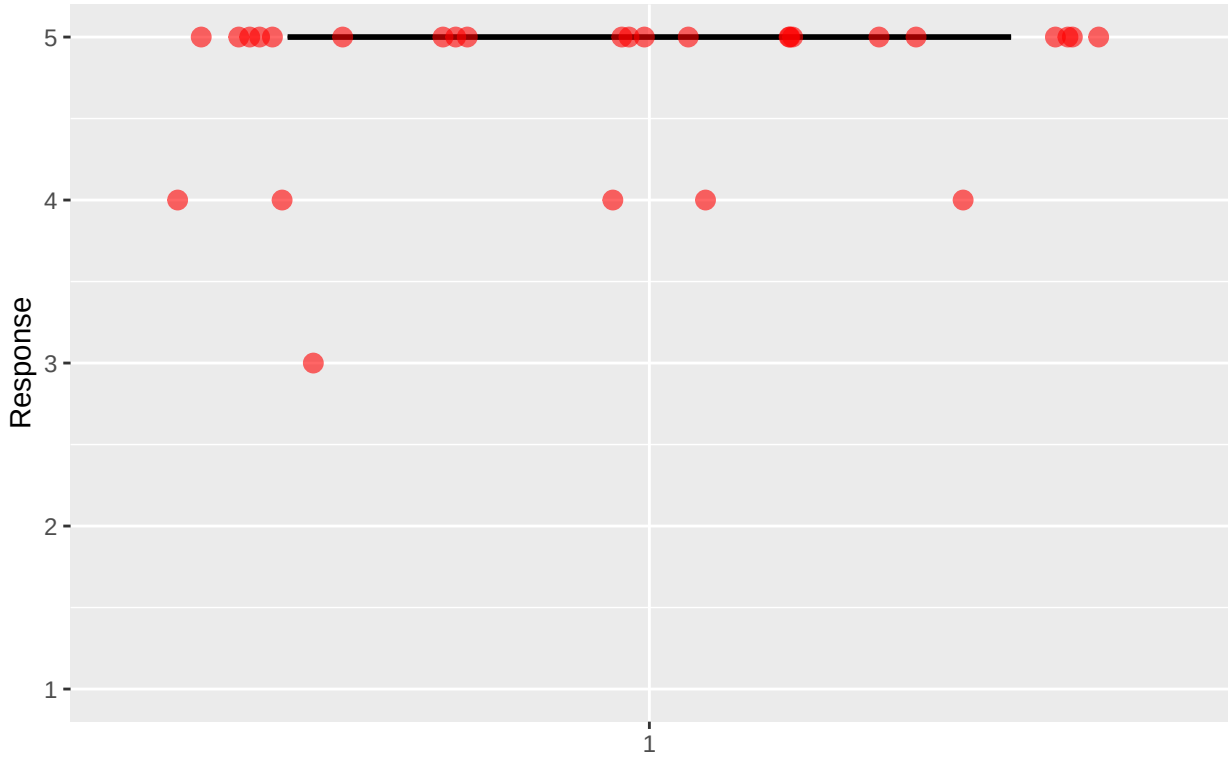

The tactile bracelet is comfortable to wear
Response
5
4
3
2
1
1

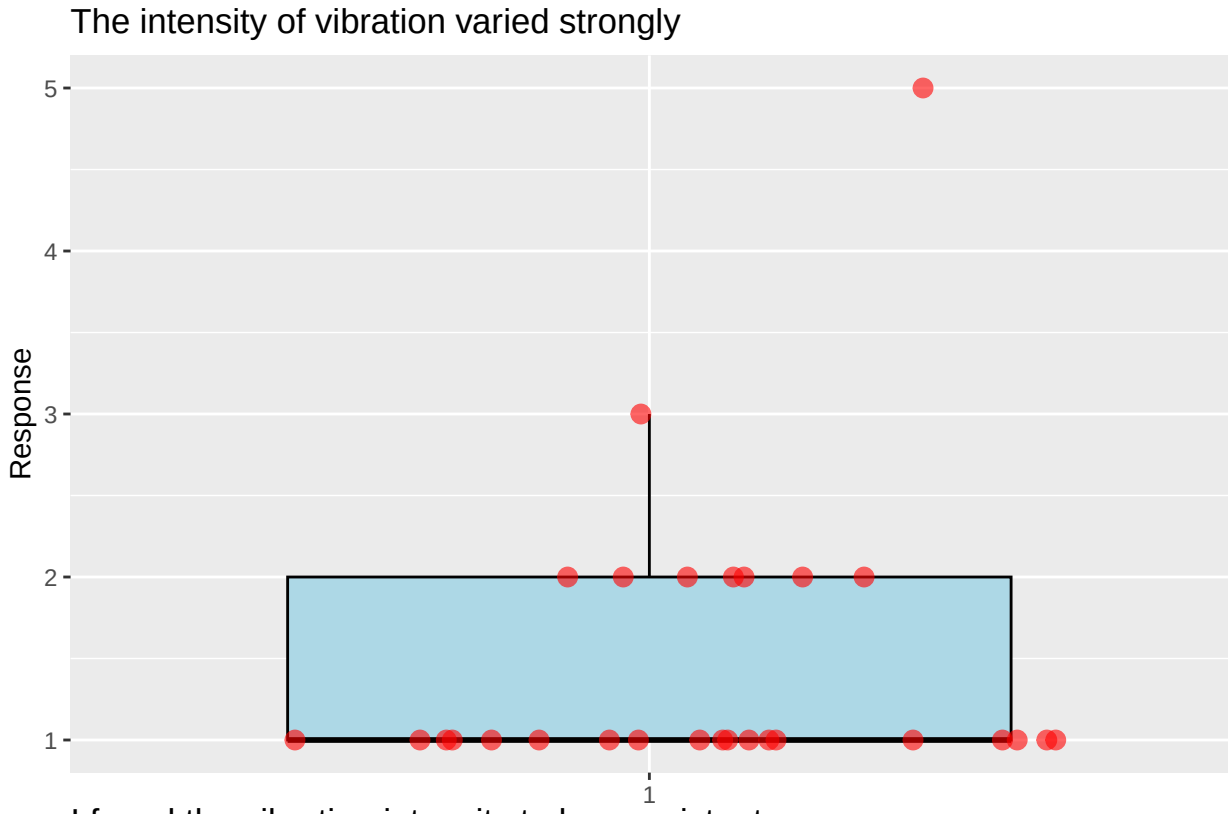

The vibration from tactile bracelet felt uncomfortable on my hand
Response
5
4
3
2
1
1

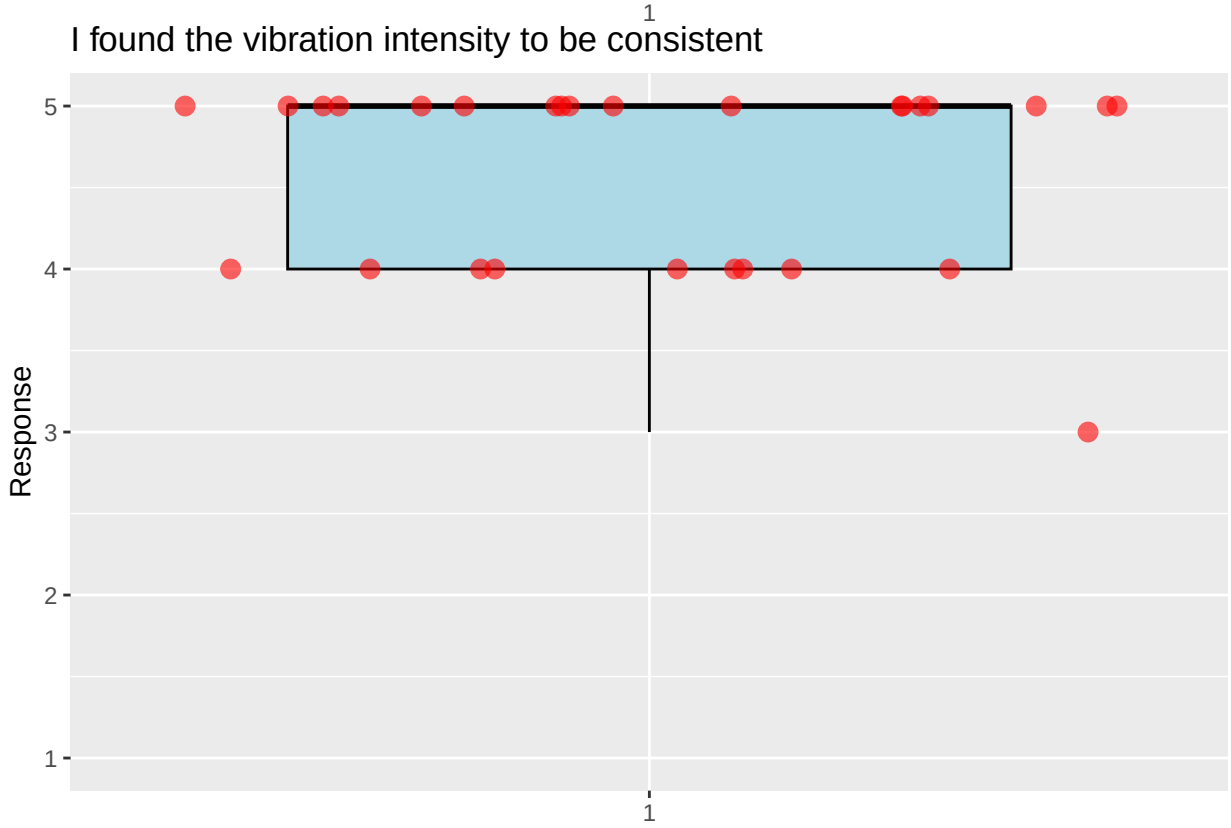
The vibration motors were positioned correctly on my arm



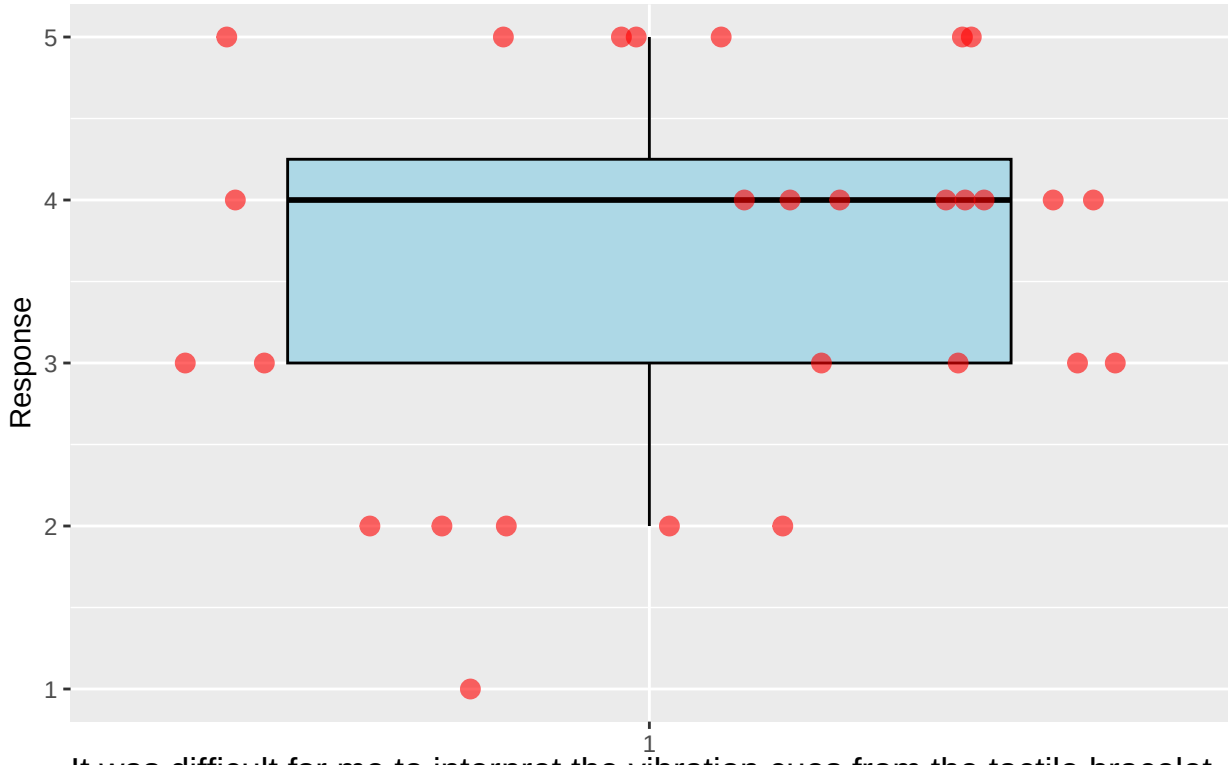
I could feel the vibration cues on my wrist from the tactile bracelet



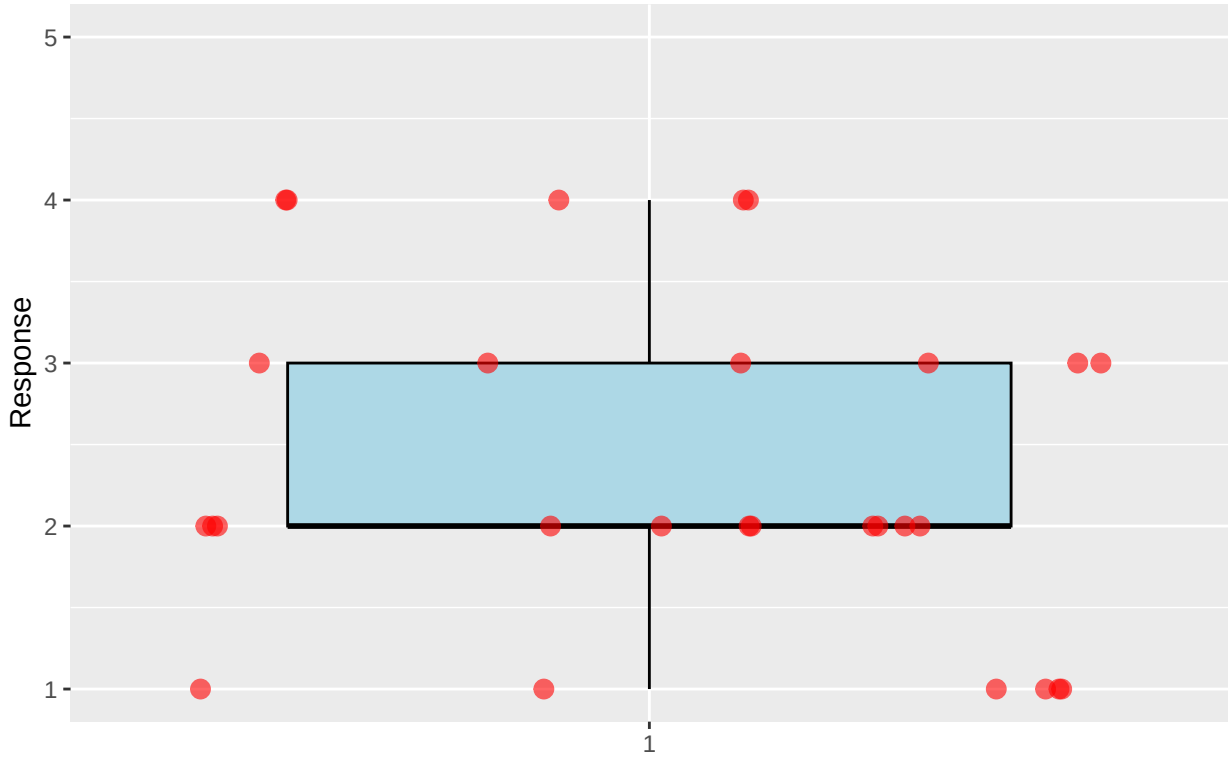

The intensity of vibration varied strongly
Response
5
4
3
2
1
1

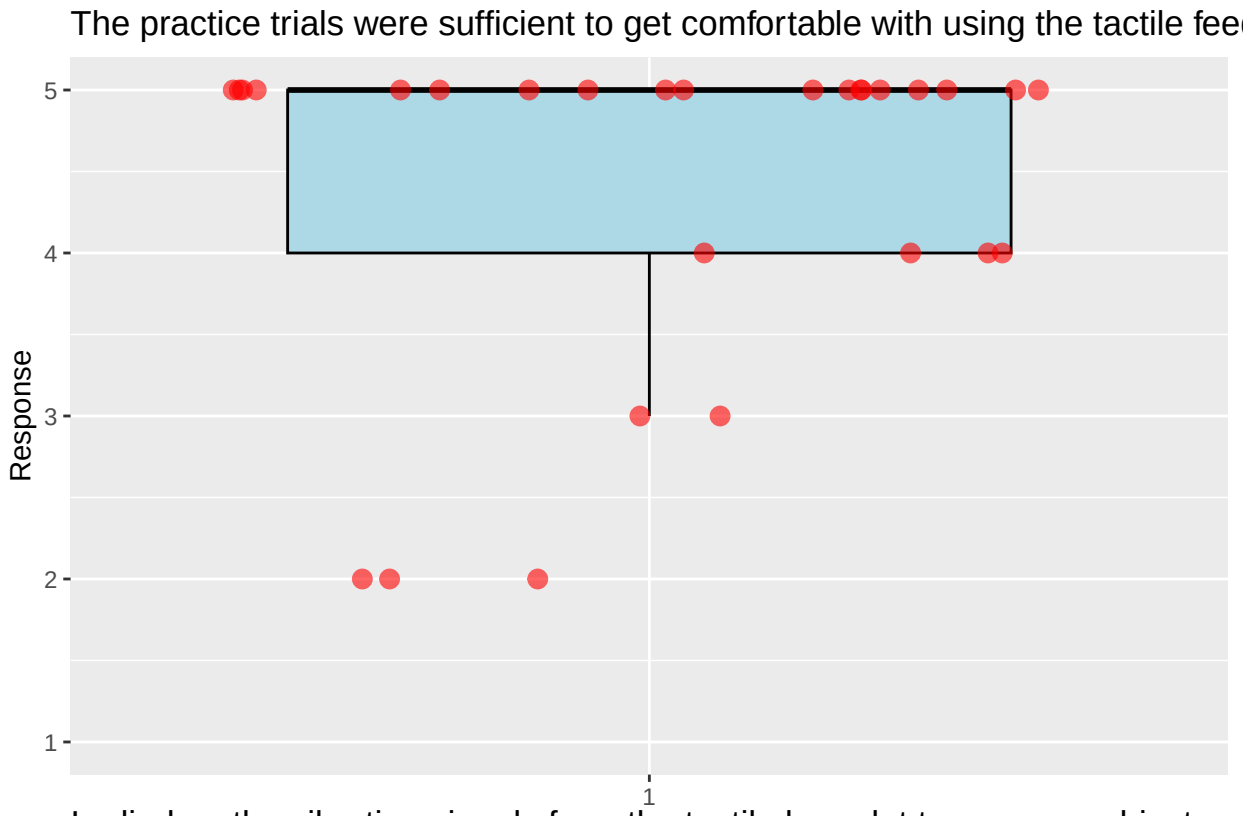

I found the vibration intensity to be consistent
Response
5
4
3
2
1
1

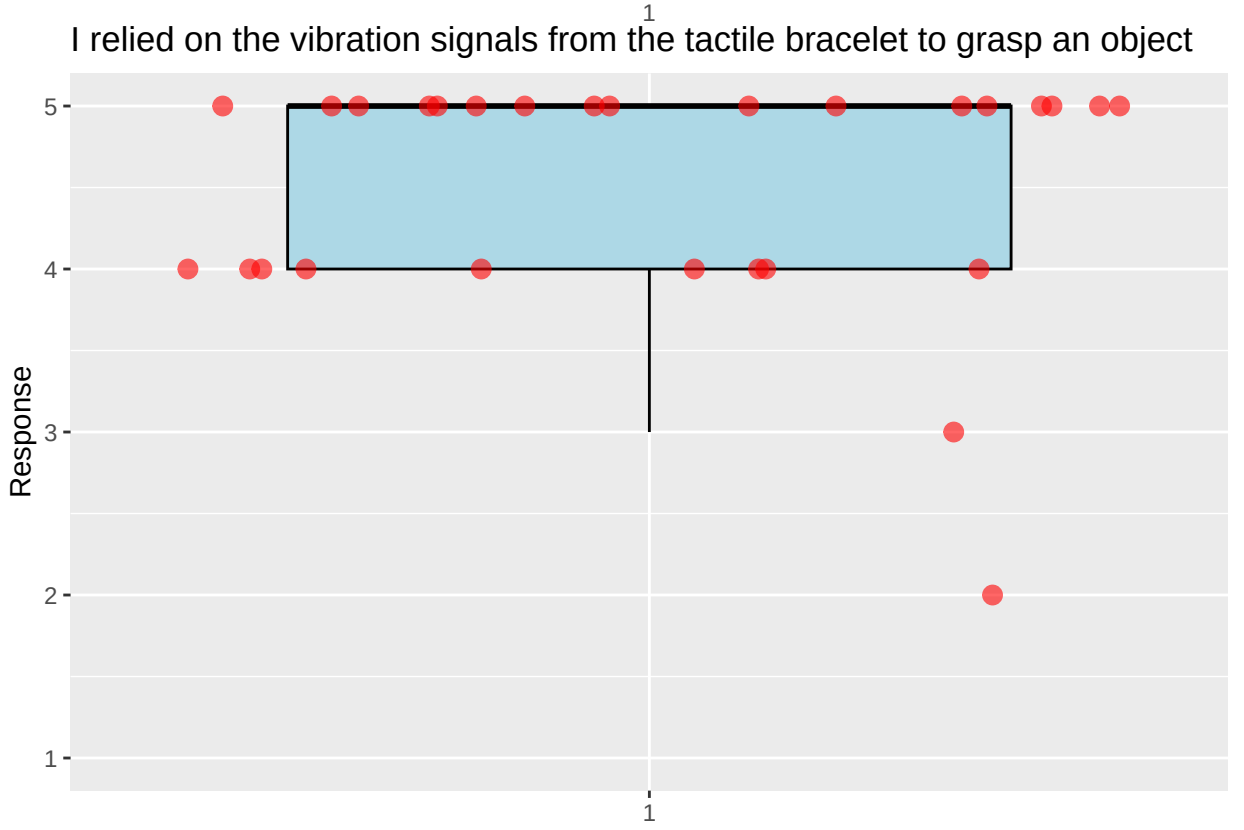
I could identify the vibration locations without much effort

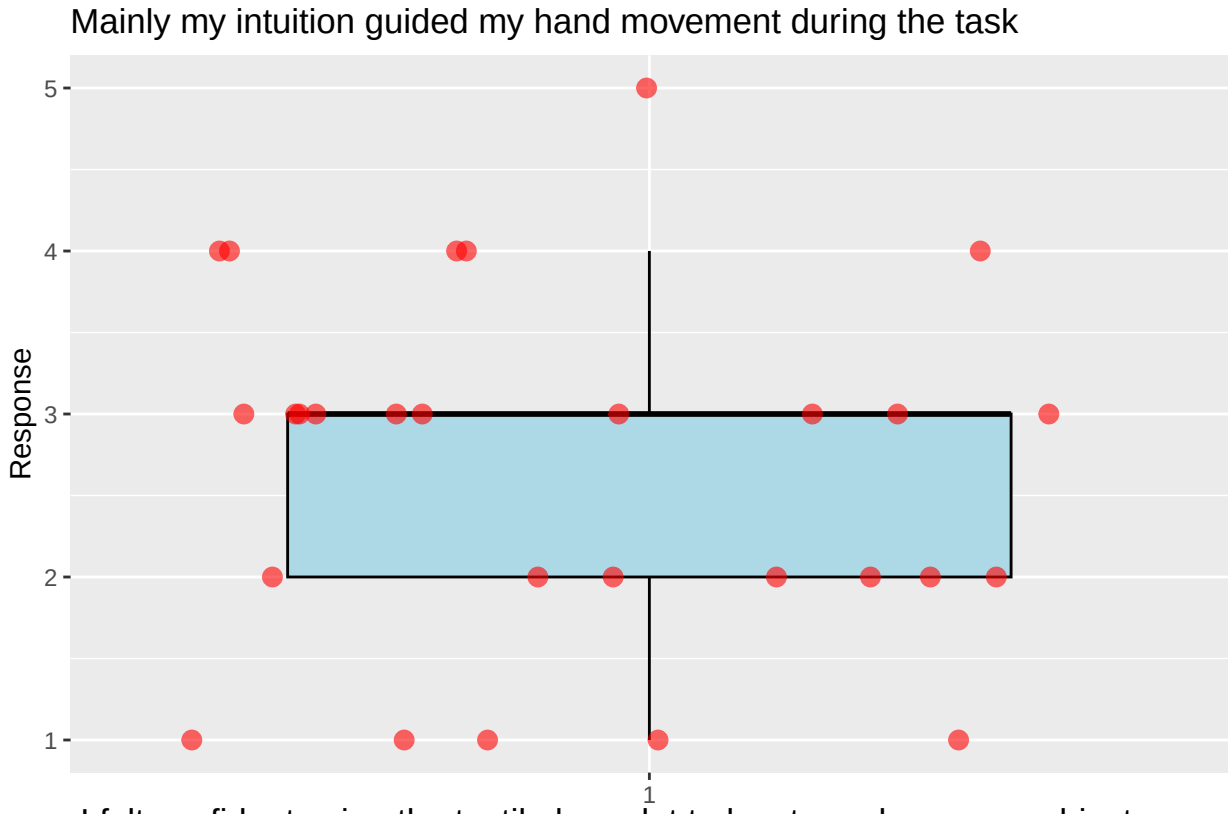


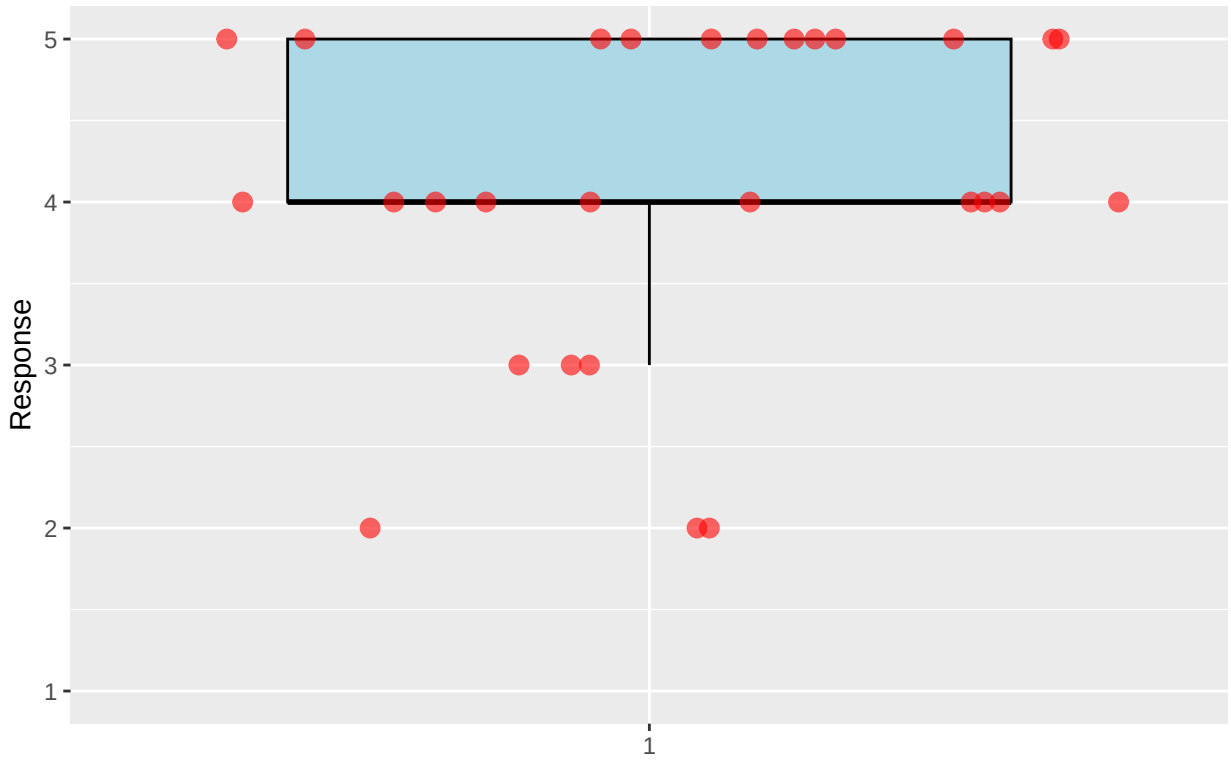
It was difficult for me to interpret the vibration cues from the tactile bracelet



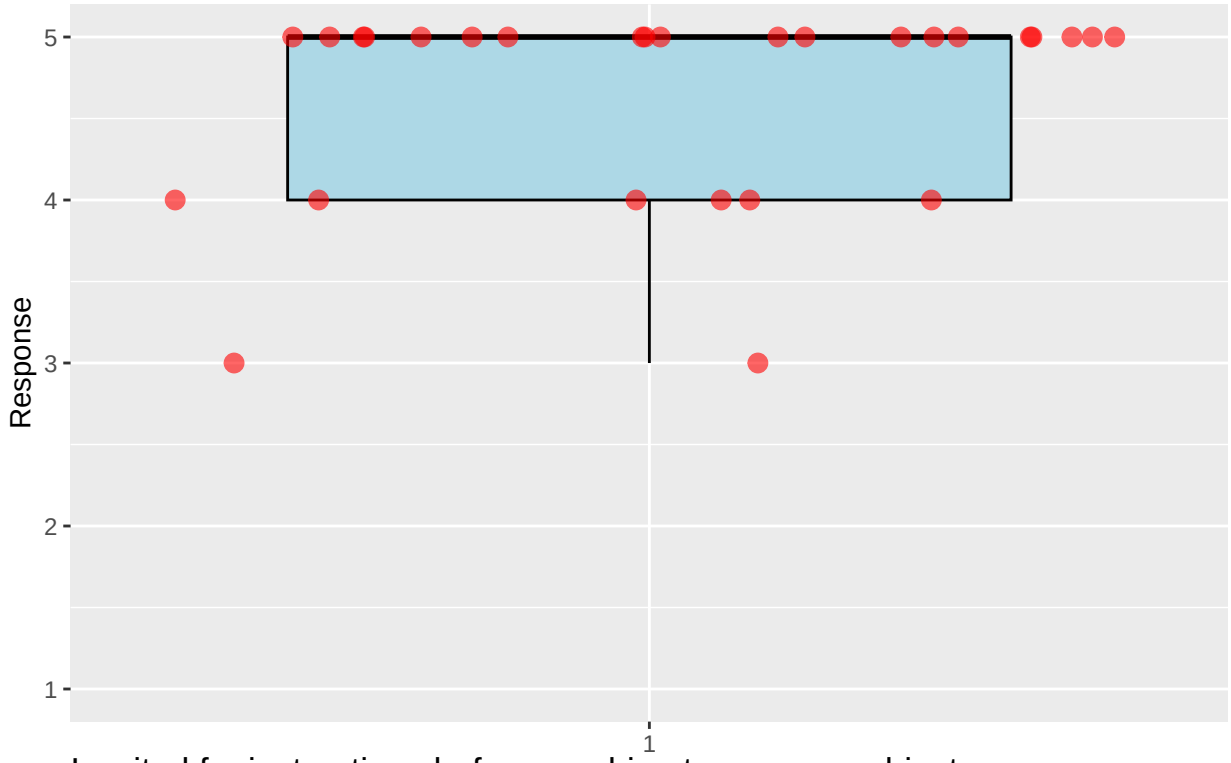

The practice trials were sufficient to get comfortable with using the tactile fee
Response
5
4
3
2
1
1


I relied on the vibration signals from the tactile bracelet to grasp an object
Response
5
4
3
2
1
1

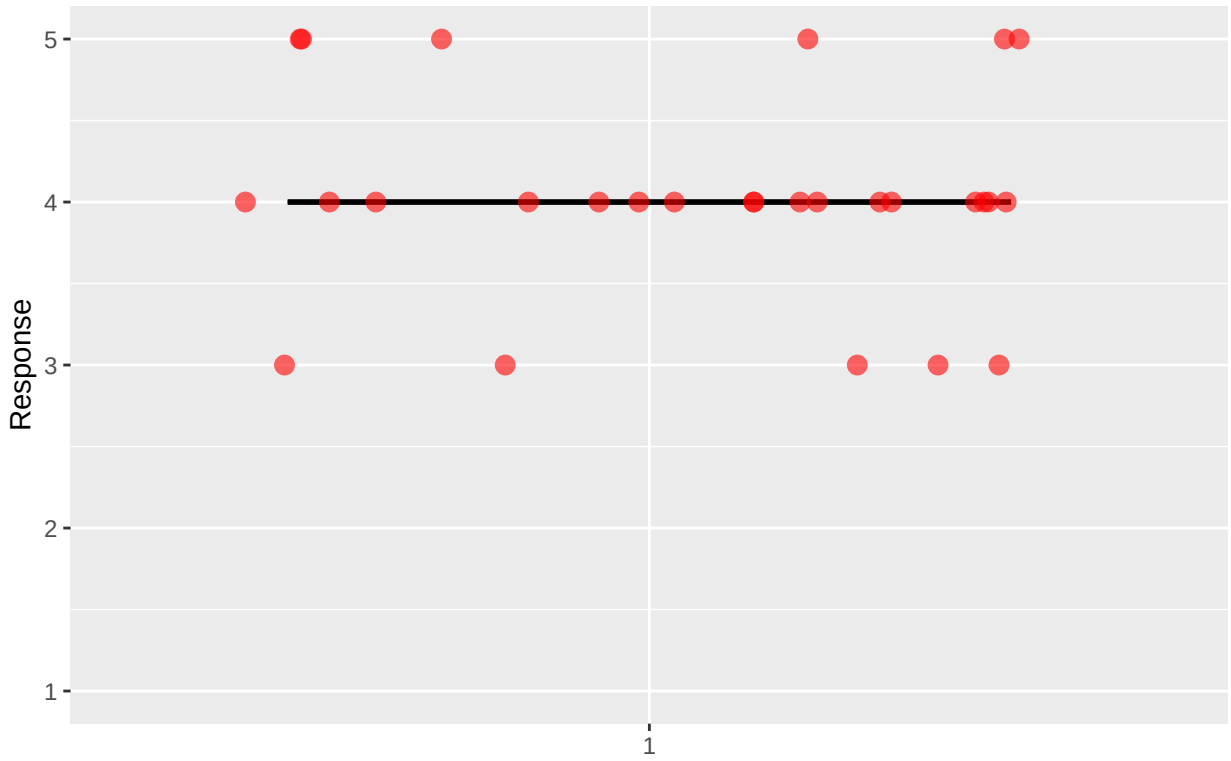

Mainly my intuition guided my hand movement during the task
Response
5
4
3
2
1
1

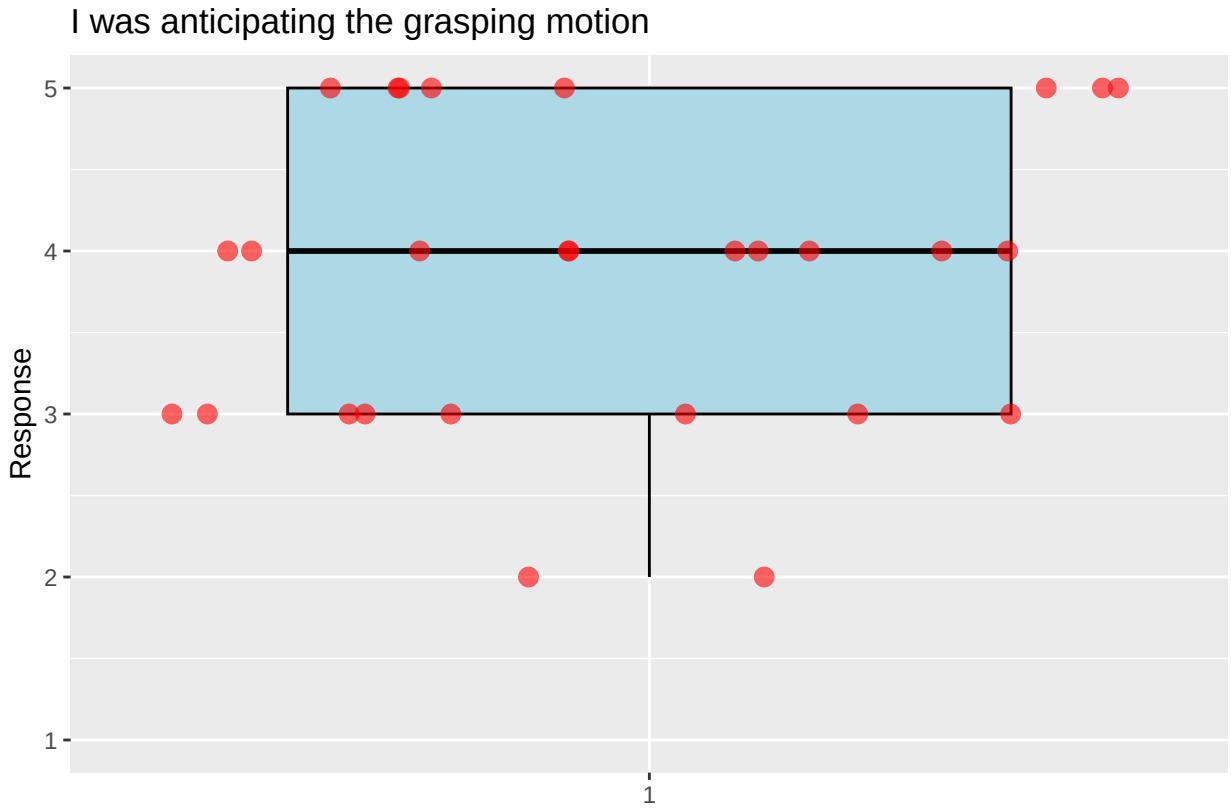

I felt confident using the tactile bracelet to locate and grasp an object
Response
5
4
3
2
1
1

I was able to develop a spatial understanding of the shelf



I waited for instructions before reaching to grasp an object





Open-ended questions

We here qualitatively analyse the comments made in the open-ended questions, regarding the experience with the tactile bracelet and the grasping task.

```
print(questionnaire_data$`Please.describe.your.general.experience.with.the.tactile.bracelet.itself..`)
```

```
##  [1] ""
##  [2] "The tacticle bracelet was easy to wear , after some time it became abit uncomfrotable maybe wi
##  [3] "The tactile bracelet was comfortable, I fairly quickly got used to it being on my hand and didn
##  [4] "It felt quite comfortable and was quite easy to follow the vibration instructions. "
##  [5] "It rested comfortably wrapped around my wrist. As soon as I started experience mild fatigue, l
##  [6] "The bracelet was comfortable to wear and interact with. It actually helped in navigating my han
##  [7] "Very comfortable. The bracelet and the stretchable support felt very stable on my wrist. The si
##  [8] "As my wrist is smaller than the average adult, I feel that the motor on the bracelet is quite l
##  [9] ""
## [10] "The vibrations given by the bracelet were helpful for locating the objects. It was quite intuit
## [11] "The tactile bracelet was good to understand. Only when up-vibrations came I was waiting a bit t
## [12] "It took a me quite a while to get used to the vibrations and not mix up the directions. Sometim
## [13] "The bracelet was comfortable to wear, though the part on  the upper arm got pretty heavy over t
## [14] "It was interesting and once you got used to it it got a little more intuitive though it was som
## [15] "The fit was alright. Tough I had to readjust the position. During the task itself I had some st
## [16] "as a prototype great, vibrations sometimes where hard to localize when the hand angle changed,
## [17] "First it was unfamiliar to rely on the vibration, but after a short time i got used to the feel
## [18] "It was an interesting new experience using the tactile bracelet. Being guided by vibrations on
## [19] "I got used to the bracelet very fast, and it was easy to let myself be guided by it. The only n
## [20] "It was a very interesting experience, and actually I felt more confortable following the instru
```

```
## [21] "It was quite comfortable to wear and, if placed right, quite helpful and clear. When not placed
## [22] "The different cues were surprisingly well distinguishable for me, though it might have been mor
## [23] "It worked well, the signals were clear and distinguishable. For the pulsing it always took a wh
## [24] "I enjoyed the process of using the tactile bracelet. It felt quite straight forward once I had
## [25] " - For relatively thin hands, it becomes more difficult to recognize the directions because the
## [26] "Many cables but not uncomfortable at all"
## [27] "Needed a bit of getting used to since I am not used to something like that but I got better at
## [28] "vibration zu gleichmäßig, auch zu groß -> räumlichkeiten schwer erfassbar (lr,ou)"
## [29] "Armband muss genau richtig adjustiert sein, sonst kann man manchmal Richtungen verwechseln."
```

Summary:
- some participants had troubles to distinguish vibration directions especially after fatigue (-> blending)
- differences in wrist circumferences can lead to perception of too large/small motors and/or vibration intensity and distinguishing directions can again be influenced by that
- grasping cue -> some participants started moving up first –> change it to something else (e.g. all motors vibrate, last direction pulses)
- some participants felt too much vibration intensity -> numbs wrist (and forearm) -> fatigues -> harder to distinguish -> less intuitive
- one P with troubles distinguishing spoken left-right reported it was easier with the bracelet

```
print(questionnaire_data$`Please.describe.your.general.experience.with.the.grasping.task`)
```

```
##  [1] ""
##  [2] "It was fun task, but navigating the shelf at the start was bit hard since I have not seen any c
##  [3] "The task itself was simple to follow. This is especially true of the verbal instruction conditi
##  [4] "Sometimes I was anticipating the "grasp" command as it became sort of a pattern, e.g. left-righ
##  [5] "I would find it more convenient if the bracelet started to pulse-vibrate as soon as my hand is
##  [6] "The task itself was easy to understand and perform. The instructions were explained to me in a
##  [7] "I loved the task. I loved it because of the amount of attention required to postulate my best p
##  [8] "I'm not sure if it's intentional, but as I continued to do the tasks, I became accustomed to th
##  [9] ""
## [10] "It was not hard or straining and honestly a bit fun. "
## [11] ""
## [12] "Some objects were harder to grasp than others and I immediately forgot which object was in whic
## [13] "I felt mostly confident during the task. The objects were mostly easy to grasp. But the grapes
## [14] "It was alright and I was able to get familiar which the setup pretty quickly. "
## [15] ""
## [16] "took a while to get used to, but then easily understood and doable. I actually started seeing t
## [17] "It was fun and a new experience to only rely on one sense. I was surprised how well i could fin
## [18] "During the grasping task, I could really feel the difference between feeling the vibration as a
## [19] "In the beginning, it became clear pretty fast that once a movement up or down was required, the
## [20] "It was ok, but maybe it would be necessary to give the instructions a bit slower, because at th
## [21] "It was in general an easy and fun task. The only comment I'd have is that some objects were har
## [22] "When I was instructed to the set up (blind already) and shown the three shelves, I actively the
## [23] "Doing the task but also trying to be as fast as possible while also moving the camera to the ri
## [24] "I definitely got more used to the motor sequence, of reaching for each object and returning to
## [25] "I think:\n\n - reference point is very important in this case because we can easily lose the ob
## [26] "Very interesting to see how you can actually get used to receiving and understanding the inform
## [27] "The task was logical & simple which helped especially when you have a vibrating device on your
## [28] "war leicht. nicht 3 sondern 4 früchte nebeneinander -> vielleicht für später"
## [29] ""
```

Summary:
- grasping anticipation because of regular pattern
- one P suggests varying vibration intensity based off of distance to target (depth)
- unnatural head movements during the task needed some attention (because of narrow camera angle)

- participants easily developed a spatial mapping of the shelf and arrangement of fruits

```
print(questionnaire_data$`Do.you.have.any.other.comments.for.us.`)
```

```
##  [1] ""
##  [2] ""
##  [3] "No"
##  [4] ""
##  [5] "Awesome work"
##  [6] ""
##  [7] "Great job with the implementation of the wrist band and nice experiment! "
##  [8] "The enjoyable tactile sensation of the fruits made the experiment quite exciting. I am not sur
##  [9] ""
## [10] "Really nice experiment leaders :))"
## [11] ""
## [12] ""
## [13] ""
## [14] ""
## [15] ""
## [16] "Thanks for the experience and the nice talk <3"
## [17] "\"Mainly my intuition guided my hand movement during the task.\" instead of being guided by th
## [18] "Not more than: I´m super invested to see where this could turn into in the future and I want t
## [19] ""
## [20] ""
## [21] ""
## [22] ""
## [23] ""
## [24] "Thanks"
## [25] "The design of a reliable system is very important because, with the decrease in trust in the s
## [26] ""
## [27] ""
## [28] "ansatz ist super, auf einem arm lassen (nicht auf zwei), lokal belassen ist gut. ist auch unau
## [29] ""
```

Questionnaire constructs

We perform latent variable inference via FA and PCA to extract underlying constructs from numerical responses to the questionnaire items.

Defining intuitive constructs

Depending on the research goals, we are defining the intuitive constructs of the questions for comparison with the analysis results.

1. **Bracelet usability**

- I felt confident using the tactile bracelet to locate and grasp an object.
- I relied on the vibration signals from the tactile bracelet to grasp an object.
- Mainly my intuition guided my hand movement during the task.
- I could identify the vibration locations without much effort.
- It was difficult for me to interpret the vibration cues from the tactile bracelet.

2. **Bracelet design** (Concept & Comfort)

- The tactile bracelet is comfortable to wear.
- The vibration from tactile bracelet felt uncomfortable on my hand.
- I could feel the vibration cues on my wrist from the tactile bracelet.
- The intensity of vibration varied strongly.
- I found the vibration intensity to be consistent.

3. **Experiment design**

- I was in fear of hitting the shelf or objects during the task.
- I felt secure during the task.
- The practice trials were sufficient to get comfortable with using the tactile feedback.
- I was able to develop a spatial understanding of the shelf.
- I waited for instructions before reaching to grasp an object.
- I was anticipating the grasping motion.
- The vibration motors were positioned correctly on my arm.

Factor Analysis

```
# remove NAs
data <- na.omit(questionnaire_data[,2:18])
```

Conduct factor analysis to explore the underlying structure of the questionnaire. This will help confirm or refine the identified constructs.

```
# remove indices
rownames(data) <- NULL

fa_model <- fa(data, nfactors = 3, rotate = "varimax", fm = "pa", max.iter = 1000)
fa_model
```

```
## Factor Analysis using method =  pa
## Call: fa(r = data, nfactors = 3, rotate = "varimax", max.iter = 1000,
##     fm = "pa")
## Standardized loadings (pattern matrix) based upon correlation matrix
##                                                                                  PA1
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                  0.25
## I.felt.secure.during.the.task.                                                  0.17
## The.tactile.bracelet.is.comfortable.to.wear.                                    0.10
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.             -0.08
## The.vibration.motors.were.positioned.correctly.on.my.arm.                       0.23
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.         -0.11
## The.intensity.of.vibration.varied.strongly.                                    -0.08
## I.found.the.vibration.intensity.to.be.consistent.                               0.18
## I.could.identify.the.vibration.locations.without.much.effort.                   0.82
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.  -0.88
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.  0.61
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.  0.31
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                    0.04
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.    0.64
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                    -0.10
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                   0.29
## I.was.anticipating.the.grasping.motion.                                        -0.32
##                                                                                  PA2
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                 -0.29
## I.felt.secure.during.the.task.                                                  0.05
```

```
## The.tactile.bracelet.is.comfortable.to.wear.                                    0.90
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.              -0.76
## The.vibration.motors.were.positioned.correctly.on.my.arm.                        0.27
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.           0.18
## The.intensity.of.vibration.varied.strongly.                                     -0.37
## I.found.the.vibration.intensity.to.be.consistent.                                0.50
## I.could.identify.the.vibration.locations.without.much.effort.                   -0.09
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.  -0.05
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.  0.15
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.  0.37
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                    -0.05
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.     0.35
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                     -0.03
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                    0.25
## I.was.anticipating.the.grasping.motion.                                          0.01
##                                                                                  PA3
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                   0.21
## I.felt.secure.during.the.task.                                                   0.20
## The.tactile.bracelet.is.comfortable.to.wear.                                     0.15
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.              -0.05
## The.vibration.motors.were.positioned.correctly.on.my.arm.                       -0.05
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.           0.04
## The.intensity.of.vibration.varied.strongly.                                     -0.48
## I.found.the.vibration.intensity.to.be.consistent.                                0.00
## I.could.identify.the.vibration.locations.without.much.effort.                    0.18
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.  0.13
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.  0.11
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.  -0.15
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                     0.74
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.     0.06
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                      0.74
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                   -0.22
## I.was.anticipating.the.grasping.motion.                                          0.30
##                                                                                   h2
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                 0.193
## I.felt.secure.during.the.task.                                                 0.072
## The.tactile.bracelet.is.comfortable.to.wear.                                   0.841
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.             0.584
## The.vibration.motors.were.positioned.correctly.on.my.arm.                      0.130
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.         0.046
## The.intensity.of.vibration.varied.strongly.                                    0.370
## I.found.the.vibration.intensity.to.be.consistent.                              0.282
## I.could.identify.the.vibration.locations.without.much.effort.                  0.715
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.  0.787
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.  0.404
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.  0.254
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                   0.550
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.   0.527
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                    0.553
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                  0.195
## I.was.anticipating.the.grasping.motion.                                        0.196
##                                                                                 u2
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                0.81
## I.felt.secure.during.the.task.                                                0.93
```

```
## The.tactile.bracelet.is.comfortable.to.wear.                                        0.16
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.                  0.42
## The.vibration.motors.were.positioned.correctly.on.my.arm.                           0.87
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.              0.95
## The.intensity.of.vibration.varied.strongly.                                         0.63
## I.found.the.vibration.intensity.to.be.consistent.                                   0.72
## I.could.identify.the.vibration.locations.without.much.effort.                       0.29
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.  0.21
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback. 0.60
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.     0.75
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                        0.45
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.        0.47
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                         0.45
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                       0.80
## I.was.anticipating.the.grasping.motion.                                             0.80
##                                                                                     com
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                      2.8
## I.felt.secure.during.the.task.                                                      2.1
## The.tactile.bracelet.is.comfortable.to.wear.                                        1.1
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.                  1.0
## The.vibration.motors.were.positioned.correctly.on.my.arm.                           2.0
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.              1.8
## The.intensity.of.vibration.varied.strongly.                                         1.9
## I.found.the.vibration.intensity.to.be.consistent.                                   1.3
## I.could.identify.the.vibration.locations.without.much.effort.                       1.1
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.  1.1
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback. 1.2
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.     2.3
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                        1.0
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.        1.6
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                         1.0
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                       2.8
## I.was.anticipating.the.grasping.motion.                                             2.0
##
##                         PA1  PA2  PA3
## SS loadings           2.73 2.32 1.66
## Proportion Var        0.16 0.14 0.10
## Cumulative Var        0.16 0.30 0.39
## Proportion Explained  0.41 0.35 0.25
## Cumulative Proportion 0.41 0.75 1.00
##
## Mean item complexity =  1.7
## Test of the hypothesis that 3 factors are sufficient.
##
## df null model =  136  with the objective function =  10.87 with Chi Square =  222.85
## df of  the model are 88  and the objective function was  6.35
##
## The root mean square of the residuals (RMSR) is  0.11
## The df corrected root mean square of the residuals is  0.14
##
## The harmonic n.obs is  28 with the empirical chi square  93.88  with prob <  0.31
## The total n.obs was  28  with Likelihood Chi Square =  117.44  with prob <  0.02
##
## Tucker Lewis Index of factoring reliability =  0.301
```

```
## RMSEA index =  0.103  and the 90 % confidence intervals are  0.047 0.161
## BIC =  -175.79
## Fit based upon off diagonal values = 0.79
## Measures of factor score adequacy
##                                                  PA1  PA2  PA3
## Correlation of (regression) scores with factors   0.95 1.00 0.90
## Multiple R square of scores with factors          0.91 1.00 0.81
## Minimum correlation of possible factor scores     0.82 0.99 0.62
```

Interpretation: We choose to select the questions of each factor with correlation equal or above 0.2 (at least slight positive correlation) and therefore come up with the following groupings:

PA1: user confidence
- I.could.identify.the.vibration.locations.without.much.effort. 0.82
- X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object. 0.64
- The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback. 0.61
- I.waited.for.instructions.before.reaching.to.grasp.an.object. 0.29
- I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task. 0.25

PA2: comfort
- The.tactile.bracelet.is.comfortable.to.wear. 0.90
- I.found.the.vibration.intensity.to.be.consistent. 0.50
- I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object. 0.37
- X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object. 0.35
- The.vibration.motors.were.positioned.correctly.on.my.arm. 0.27
- I.waited.for.instructions.before.reaching.to.grasp.an.object. 0.25

PA3: learning / intuition
- Mainly.my.intuition.guided.my.hand.movement.during.the.task. 0.74
- I.was.able.to.develop.a.spatial.understanding.of.the.shelf. 0.74
- I.was.anticipating.the.grasping.motion. 0.30
- I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task. 0.21
- I.felt.secure.during.the.task. 0.20

Principal Component Analysis

We perform PCA (dimensionality reduction) to extract the PCs that explain more than half the variance in the data, possible more.

```r
# function for displaying each PC and its ordered correlation coefficients
# returns the correlation matrices after PCA and reconstructed
extract_PC <- function(data, n_comps, thres=-1){
  # normalize data and perform PCA
  corr_matrix <- cor(scale(data))
  data.pca <- princomp(corr_matrix)
  print(summary(data.pca))
  # extract correlation loadings
  loadings <- data.pca$loadings[, 0:n_comps]

  # output each PC
  for (i in 1:n_comps) {
    print(data.frame(item=loadings[,0], PC=loadings[,i]) %>% arrange(desc(PC)) %>% filter(PC >= thres))
  }

  # use different PCA method for data reconstruction
  res <- prcomp(data, scale. = TRUE)
```

```r
  corr_matrix_reconstructed <- cor(res$x[, 0:n_comps] %*% t(res$rotation[, 0:n_comps]))

  return(list("pca" = res, "loadings" = loadings, "normal" = corr_matrix, "reconstructed" = corr_matrix
}

# extract 3 PCs
res <- extract_PC(data, 3)
```

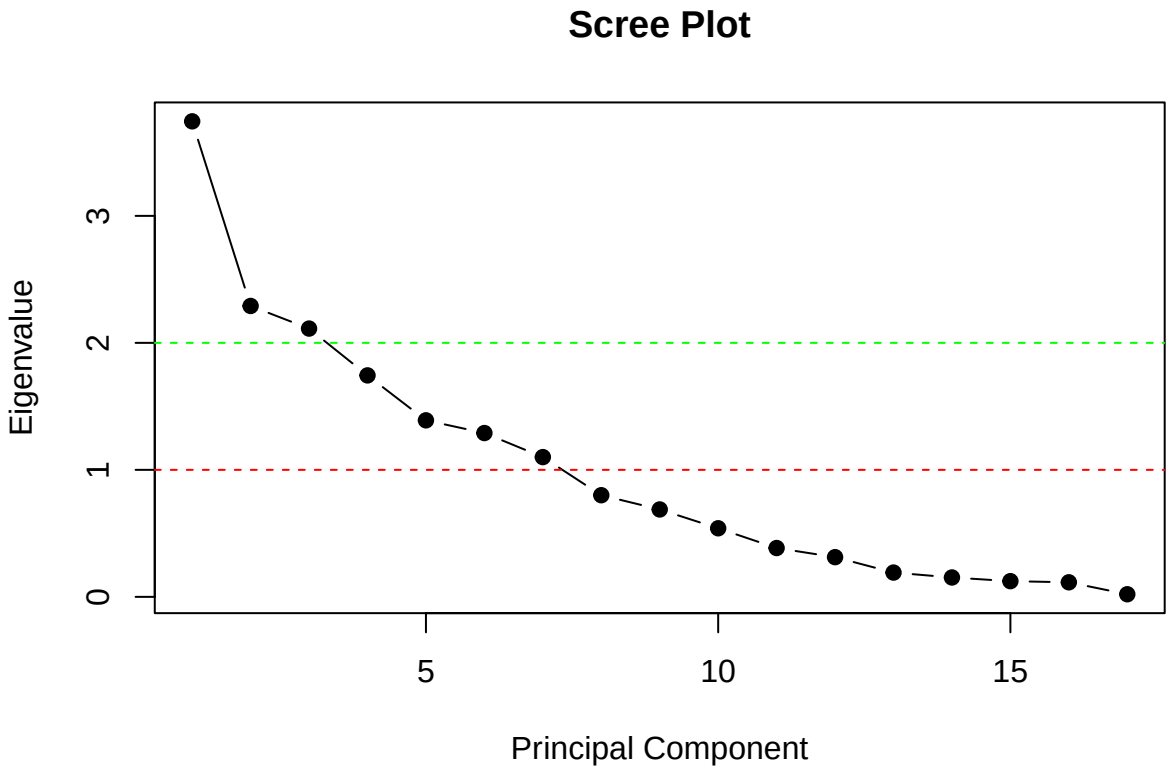
```
## Importance of components:
##                            Comp.1    Comp.2    Comp.3     Comp.4     Comp.5
## Standard deviation     0.8530053 0.5472489 0.4850658 0.41773511 0.33597323
## Proportion of Variance 0.4028554 0.1658118 0.1302708 0.09661569 0.06249641
## Cumulative Proportion  0.4028554 0.5686672 0.6989380 0.79555371 0.85805012
##                            Comp.6     Comp.7     Comp.8     Comp.9     Comp.10
## Standard deviation     0.29840242 0.26624325 0.19402404 0.15772818 0.127277428
## Proportion of Variance 0.04930039 0.03924668 0.02084284 0.01377413 0.008969092
## Cumulative Proportion  0.90735051 0.94659719 0.96744002 0.98121416 0.990183249
##                           Comp.11     Comp.12     Comp.13      Comp.14
## Standard deviation     0.093026327 0.071787012 0.044070948 0.0330795902
## Proportion of Variance 0.004791345 0.002853234 0.001075352 0.0006058512
## Cumulative Proportion  0.994974594 0.997827829 0.998903180 0.9995090316
##                            Comp.15      Comp.16      Comp.17
## Standard deviation     0.0280499033 9.998322e-03 7.276234e-09
## Proportion of Variance 0.0004356206 5.534774e-05 2.931292e-17
## Cumulative Proportion  0.9999446523 1.000000e+00 1.000000e+00
##                                                                                                  PC
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.       0.375967871
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.                       0.300459361
## I.was.anticipating.the.grasping.motion.                                                  0.206256958
## The.intensity.of.vibration.varied.strongly.                                              0.156599294
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                              0.099180133
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                             0.040860404
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.                   0.024596184
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                           0.005783302
## I.felt.secure.during.the.task.                                                          -0.066551560
## The.vibration.motors.were.positioned.correctly.on.my.arm.                               -0.207696477
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                           -0.258551588
## I.found.the.vibration.intensity.to.be.consistent.                                       -0.268188527
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.         -0.295964998
## I.could.identify.the.vibration.locations.without.much.effort.                           -0.297870013
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback. -0.301581712
## The.tactile.bracelet.is.comfortable.to.wear.                                            -0.311940148
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.            -0.371808303
##                                                                                                  PC
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.                        0.36371516
## The.intensity.of.vibration.varied.strongly.                                               0.34085796
## I.could.identify.the.vibration.locations.without.much.effort.                             0.29493942
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                            0.27848321
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.  0.15671240
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                             0.09839861
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.              0.03929414
## I.felt.secure.during.the.task.                                                           -0.03200846
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.          -0.04453649
## The.vibration.motors.were.positioned.correctly.on.my.arm.                                -0.06378164
```

```
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                                -0.16170717
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.                      -0.19881050
## I.found.the.vibration.intensity.to.be.consistent.                                           -0.24097158
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                                 -0.24635718
## I.was.anticipating.the.grasping.motion.                                                     -0.28677297
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.          -0.31577132
## The.tactile.bracelet.is.comfortable.to.wear.                                                -0.42159161
##                                                                                                     PC
## Mainly.my.intuition.guided.my.hand.movement.during.the.task.                                 0.55242274
## I.was.able.to.develop.a.spatial.understanding.of.the.shelf.                                  0.47816746
## I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.                               0.37220932
## I.could.identify.the.vibration.locations.without.much.effort.                                0.28900607
## The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.     0.16286288
## I.felt.secure.during.the.task.                                                               0.14393529
## I.was.anticipating.the.grasping.motion.                                                      0.06845565
## The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.                           0.06465125
## X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.                 0.04650658
## The.tactile.bracelet.is.comfortable.to.wear.                                                -0.06137651
## It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.          -0.07300615
## I.found.the.vibration.intensity.to.be.consistent.                                           -0.09319843
## The.vibration.motors.were.positioned.correctly.on.my.arm.                                   -0.10583295
## I.waited.for.instructions.before.reaching.to.grasp.an.object.                               -0.10684810
## I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.                      -0.13796061
## I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.             -0.14880593
## The.intensity.of.vibration.varied.strongly.                                                 -0.32291457
```

```
eigenvalues <- res$pca$sdev^2
#retained_components <- sum(eigenvalues > 1)
eigenvalues
```

```
##  [1] 3.74424094 2.29056748 2.11265916 1.74392591 1.38995099 1.28989996
##  [7] 1.10051290 0.80034504 0.68819299 0.53996881 0.38446326 0.31255473
## [13] 0.19121521 0.15261372 0.12360567 0.11466227 0.02062095
```

```
plot(eigenvalues, type = "b", pch = 19, xlab = "Principal Component", ylab = "Eigenvalue", main = "Scree
abline(h = 1, col = "red", lty = 2)
abline(h = 2, col = "green", lty = 2)
```




```
print(paste0("Number of PCs with EV > 1: ", sum(eigenvalues > 1)))
```

```
## [1] "Number of PCs with EV > 1: 7"
```

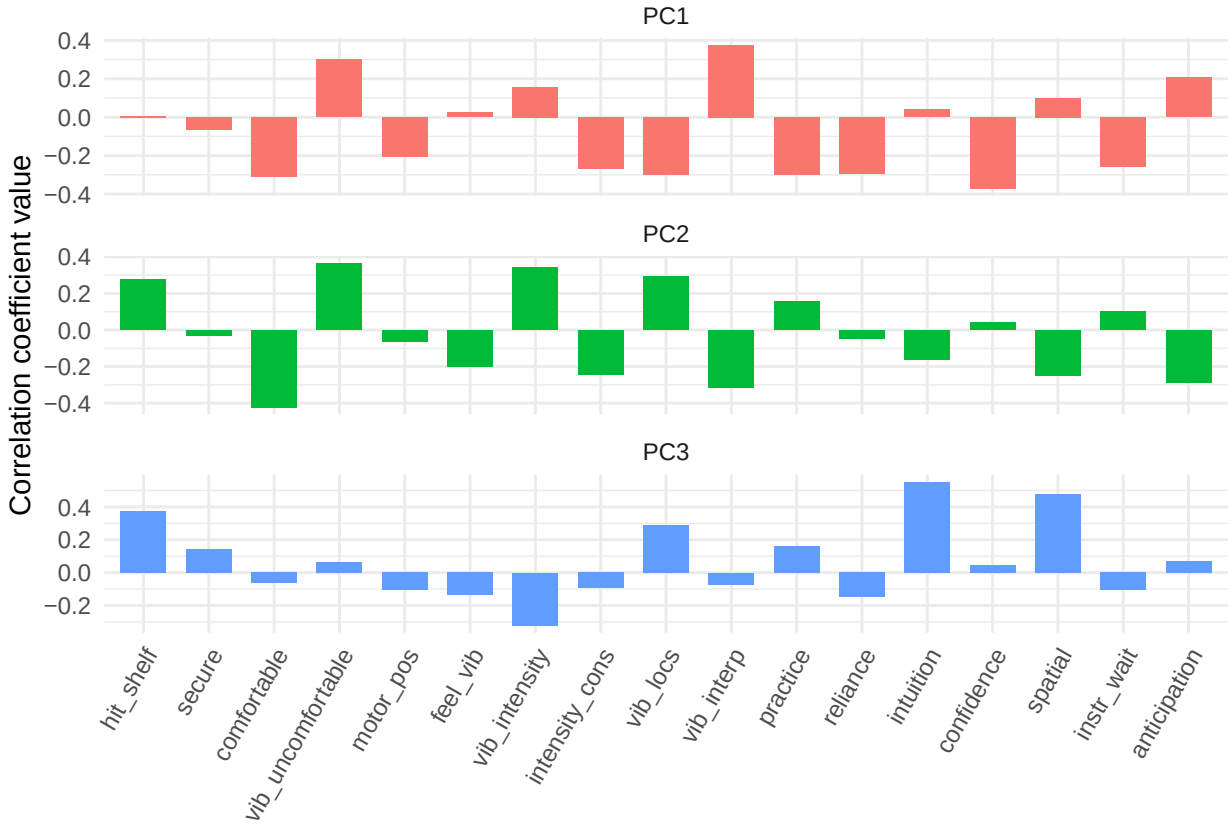
```
print(paste0("Number of PCs with EV > 2: ", sum(eigenvalues > 2)))
```

```
## [1] "Number of PCs with EV > 2: 3"
```

In this case, 2 PCs explain ~57%, 3 PCs ~70% of the variance in the data. The screeplot shows cut-off lines for eigenvalues > 1 and 2, following Kaiser's stopping rule. 7 PCs lie above Kaiser's EV of 1, explaining ~95% of the variance. We here choose 3 PCs, as these are the ones above EV of 2, and it lines up with our a priori selection for the questionnaire design. This indicates that the questions were not formulated in a way such that a single question exclusively investigates one of the intuitive groupings but as 3 PCs explain more than 70% of cumulative variance and afterwards explained-variance differences are lower than 10%, we confidently stick to 3 PCs.

```
# shorten question names
qs <- c("hit_shelf", "secure", "comfortable", "vib_uncomfortable", "motor_pos", "feel_vib", "vib_intens

#qs <- c("fear_of_hitting_shelf", "sense_of_task_security", "bracelet_comfort", "vibration_discomfort",

pcs <- data.frame(Question = rownames(res$loadings), PC1=res$loadings[,1], PC2=res$loadings[,2], PC3=res
# convert to long format
pcs <- pcs %>% pivot_longer(cols = starts_with("PC"), names_to = "PC", values_to = "Value")
pcs$Question <- factor(pcs$Question, levels = rownames(res$loadings))

# Create a faceted barplot
loads <- ggplot(pcs, aes(x = Question, y = Value, fill = PC)) +
  geom_bar(stat = "identity", width = 0.7) +
  labs(#title = "Component loadings of first 3 PCs",
       x = NULL,
```

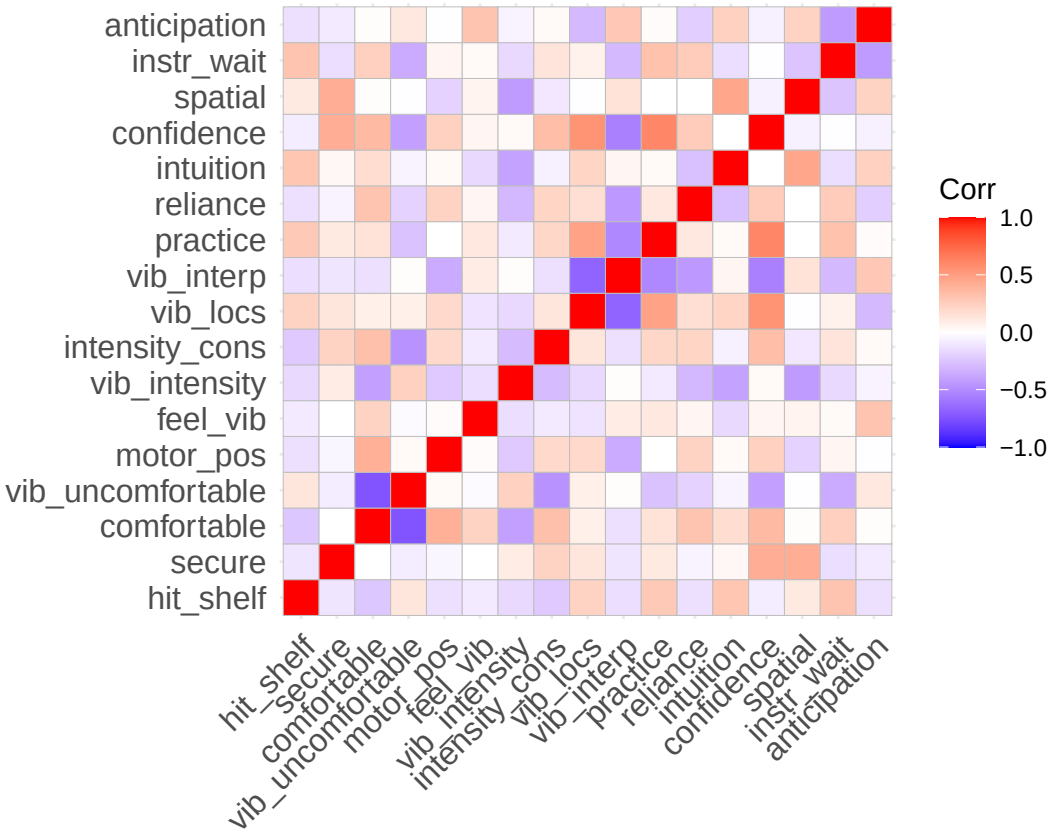
```
      y = "Correlation coefficient value") +
  facet_wrap(~ PC, scales = "free_y", ncol = 1) +
  theme_minimal() +
  theme(legend.position = "none", axis.text.x = element_text(angle = 60, hjust = 1)) +
  scale_x_discrete(labels = qs)
loads
```



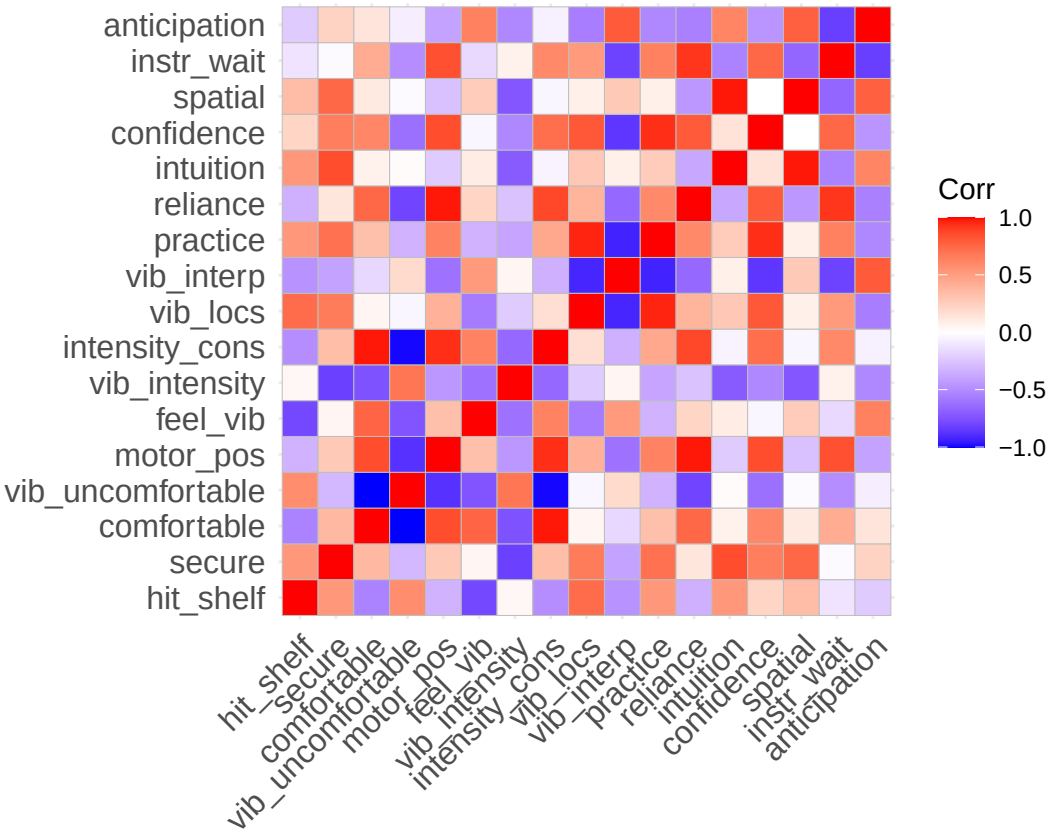

```
#ggsave(paste0(SAVE,"comp_loadings.jpeg"), plot = loads, dpi = 600)
```

We then plot the correlation matrices after PCA, of the reconstructed data and re-ordered (using hierarchical clustering) to visualize the PCs (Kording et al., 2018).

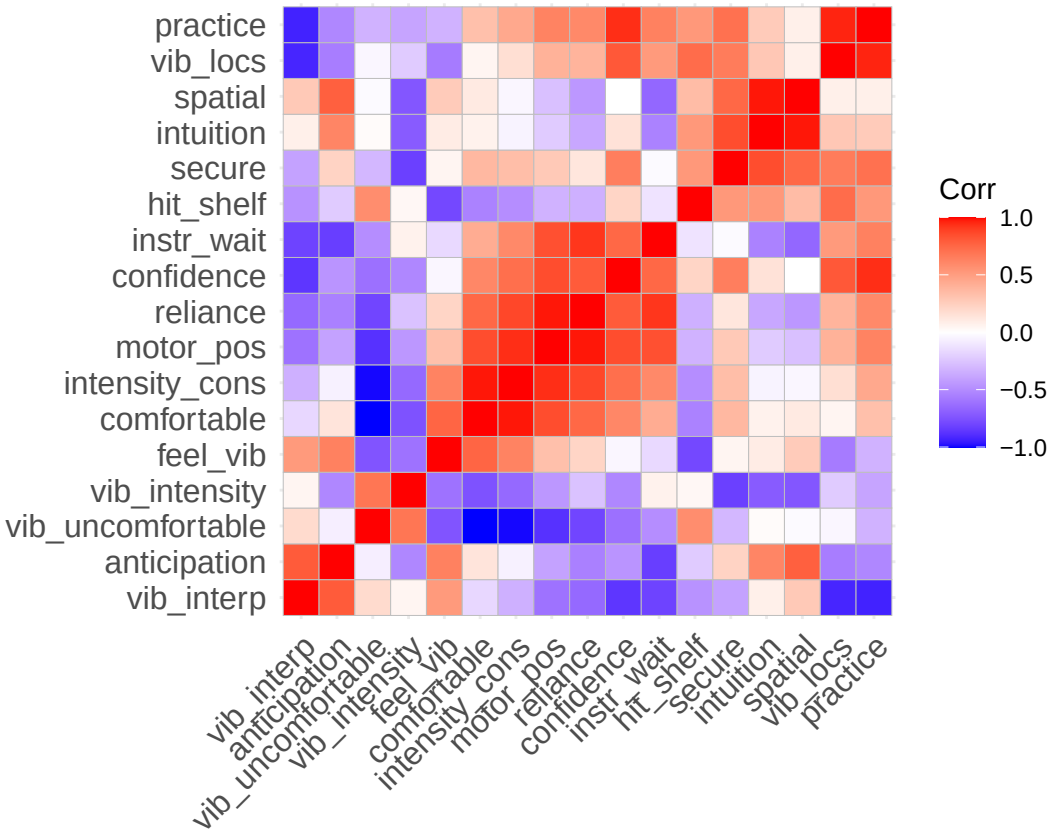
```
# comfortable, intensity_cons, feel_vib, motor_pos, reliance, confidence, instr_wait

# plot corr matrix after pca
pca_before <- ggcorrplot(res$normal) +
  scale_x_discrete(labels = qs) +
  scale_y_discrete(labels = qs)
pca_before
```




```
# plot reconstructed corr matrix
pca_after <- ggcorrplot(res$reconstructed) +
  scale_x_discrete(labels = qs) +
  scale_y_discrete(labels = qs)
pca_after
```




```
# Perform hierarchical clustering and get order
#hclust_result <- hclust(dist(res$reconstructed))
#order <- hclust_result$order
order <- c(10,17,4,7,6,3,8,5,12,14,16,1,2,13,15,9,11) # re-order to visualize the 3 PCs
corr_reordered <- res$reconstructed[order,order]

# plot re-ordered reconstructed corr matrix
reordered <- ggcorrplot(corr_reordered) +
  scale_x_discrete(labels = qs[order]) +
  scale_y_discrete(labels = qs[order])
reordered
```




```
#ggsave(paste0(SAVE,"corr_mat_reordered.jpeg"), plot = reordered, dpi = 600)
```

Interpretation

Question keys
- 1 hit_shelf: I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task.
- 2 secure: I.felt.secure.during.the.task.
- 3 comfortable: The.tactile.bracelet.is.comfortable.to.wear.
- 4 vib_uncomfortable: The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand.
- 5 motor_pos: The.vibration.motors.were.positioned.correctly.on.my.arm.
- 6 feel_vib: I.could.feel.the.vibration.cues.on.my.wrist.from.the.tactile.bracelet.
- 7 vib_intensity: The.intensity.of.vibration.varied.strongly.
- 8 intensity_cons: I.found.the.vibration.intensity.to.be.consistent.
- 9 vib_locs: I.could.identify.the.vibration.locations.without.much.effort.
- 10 vib_interp: It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet.
- 11 practice: The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback.
- 12 reliance: I.relied.on.the.vibration.signals.from.the.tactile.bracelet.to.grasp.an.object.
- 13 intuition: Mainly.my.intuition.guided.my.hand.movement.during.the.task.
- 14 confidence: X.I.felt.confident.using.the.tactile.bracelet.to.locate.and.grasp.an.object.
- 15 spatial: I.was.able.to.develop.a.spatial.understanding.of.the.shelf.
- 16 instr_wait: I.waited.for.instructions.before.reaching.to.grasp.an.object.
- 17 anticipation: I.was.anticipating.the.grasping.motion.

PC1: bracelet usability
- It.was.difficult.for.me.to.interpret.the.vibration.cues.from.the.tactile.bracelet. 0.38 - The.vibration.from.tactile.bracelet.felt.unc
0.30
- I.was.anticipating.the.grasping.motion. 0.21

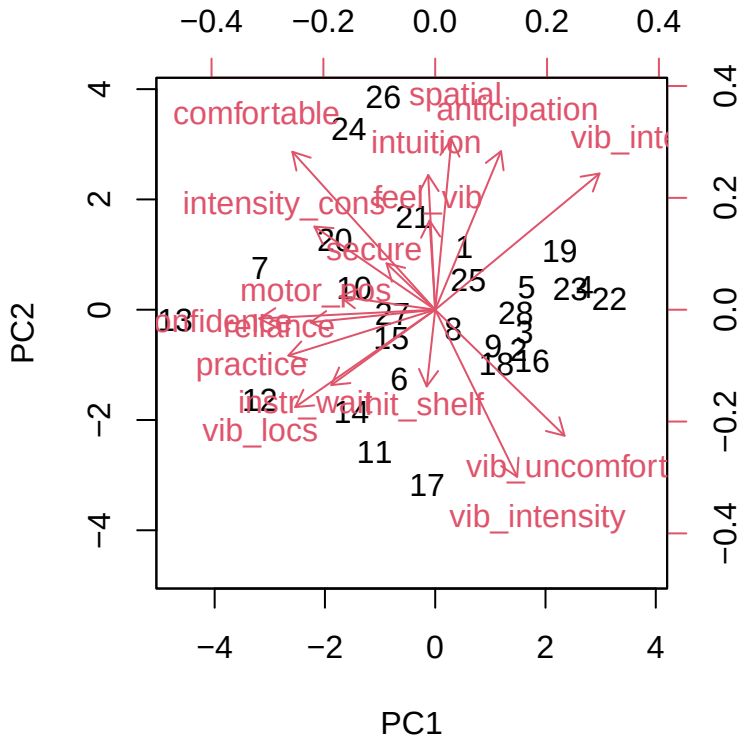
- The.intensity.of.vibration.varied.strongly. 0.16

PC2: task & bracelet confidence
- The.vibration.from.tactile.bracelet.felt.uncomfortable.on.my.hand. 0.36 - The.intensity.of.vibration.varied.strongly. 0.34
- I.could.identify.the.vibration.locations.without.much.effort. 0.29
- I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task. 0.28
- The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback. 0.16

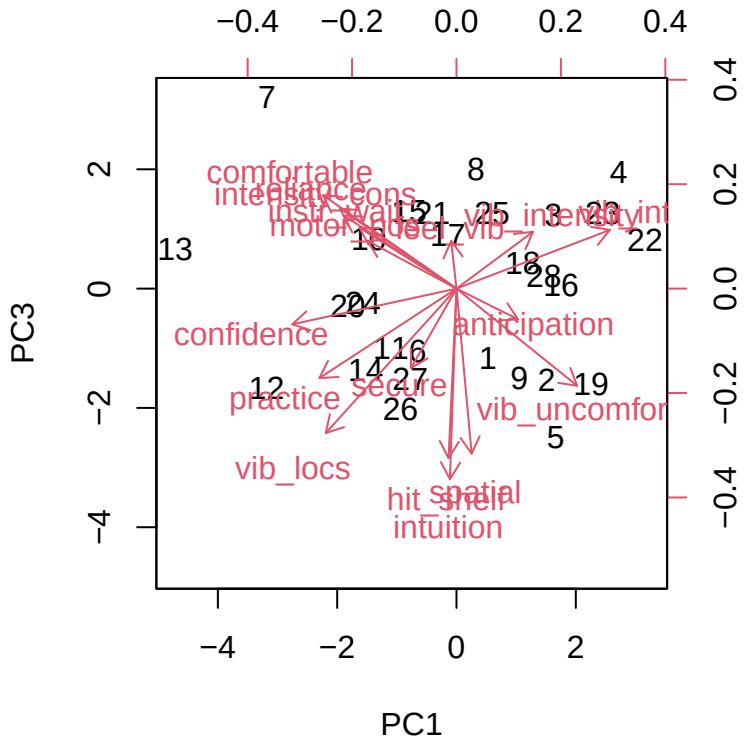
PC3: learning intuition
- Mainly.my.intuition.guided.my.hand.movement.during.the.task. 0.55 - I.was.able.to.develop.a.spatial.understanding.of.the.shelf 0.48
- I.was.in.fear.of.hitting.the.shelf.or.objects.during.the.task. 0.37
- I.could.identify.the.vibration.locations.without.much.effort. 0.29
- The.practice.trials.were.sufficient.to.get.comfortable.with.using.the.tactile.feedback. 0.16
- I.felt.secure.during.the.task. 0.14

Visualize PCs

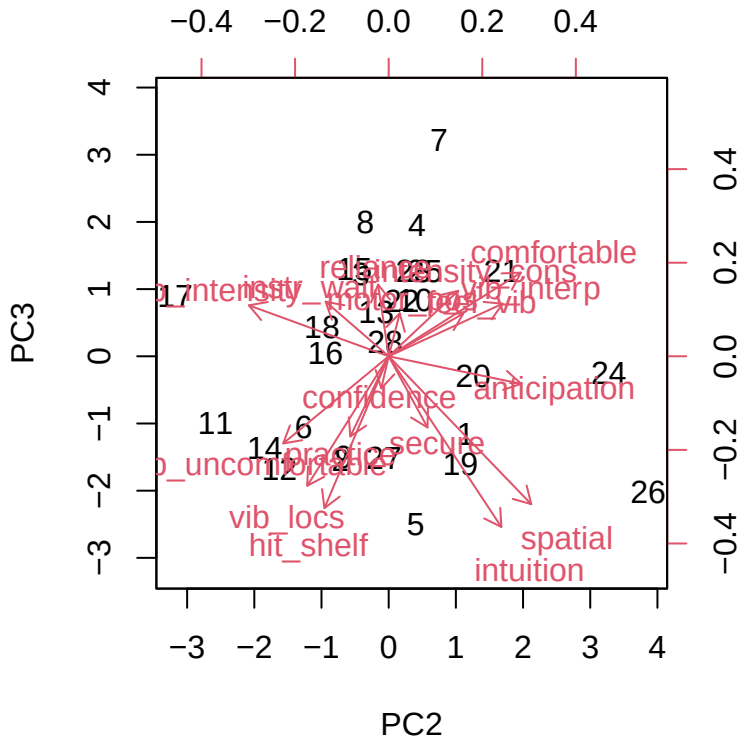
```
# https://www.statology.org/principal-components-analysis-in-r/

# bi-plot
res$pca$x <- -1*res$pca$x
biplot(res$pca, scale = 0, ylabs = qs) # 1 vs 2
```



```r
biplot(res$pca, choices = c(1, 3), scale = 0, ylabs=qs) # 1 vs 3
```




```r
biplot(res$pca, choices = c(2, 3), scale = 0, ylabs=qs) # 2 vs 3
```




```r
# Summary statistics
```

Data preparation

We clean the data and wrangle it into another format

```
clean_data <- data.frame()
for (col in colnames(questionnaire_data)[2:18]) {
  questions <- data.frame(Response = questionnaire_data[, col], Question = gsub("\\.", " ", col))
  title <- gsub("^X", "", col)
  title <- gsub("\\.", " ", title)
  clean_data <- rbind(clean_data, questions[-1,])
}
rownames(clean_data) <- NULL

# rename one question (remove preceding 'X')
clean_data[clean_data$Question == "X I felt confident using the tactile bracelet to locate and grasp an
```

Add underlying constructs.

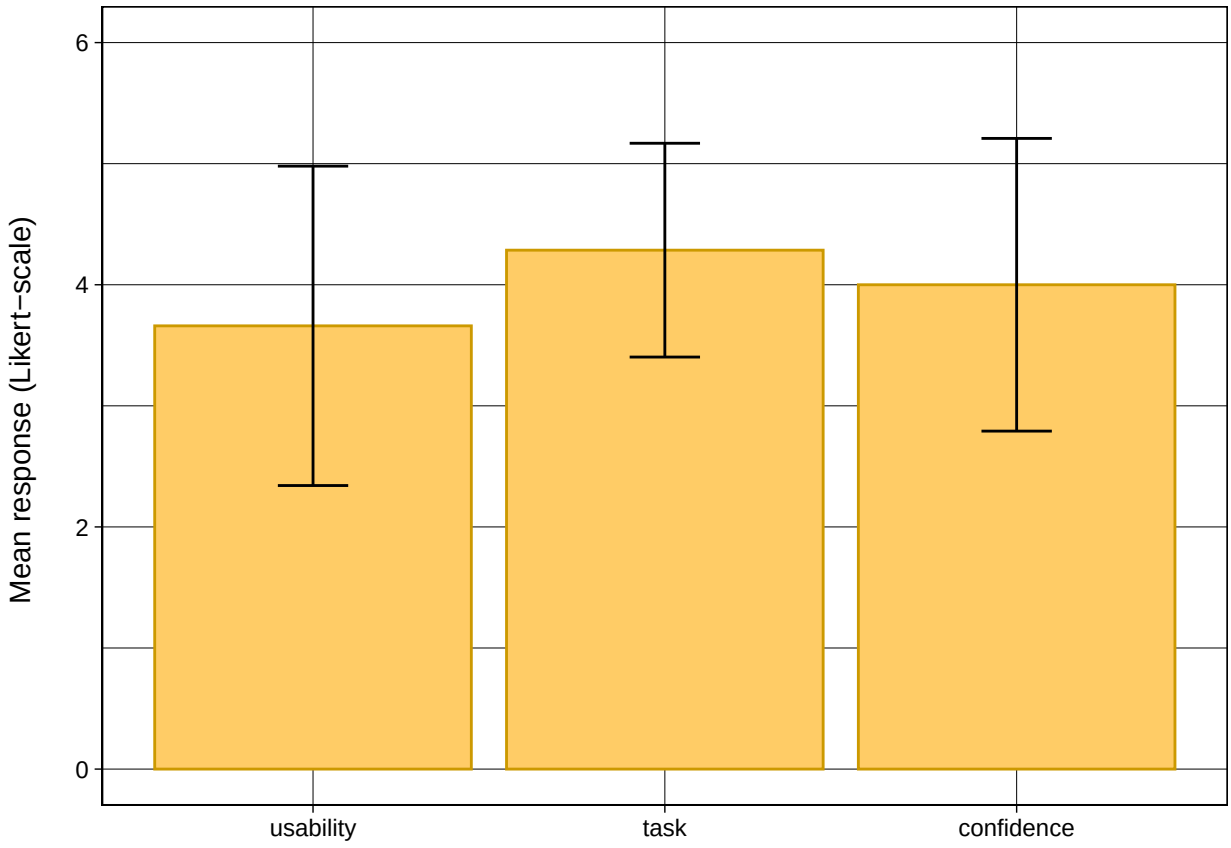
```
coded_data <- clean_data

# PC1: tactile signals, usability, interpretability
usability <- c(
  "The intensity of vibration varied strongly ",
  "The vibration from tactile bracelet felt uncomfortable on my hand ",
  "I was anticipating the grasping motion ",
  "It was difficult for me to interpret the vibration cues from the tactile bracelet "
)

# PC2: experimental design, bracelet design, consistency
task <- c(
  "I could feel the vibration cues on my wrist from the tactile bracelet ",
  "The tactile bracelet is comfortable to wear ",
  "I found the vibration intensity to be consistent ",
  "The vibration motors were positioned correctly on my arm ",
  "I relied on the vibration signals from the tactile bracelet to grasp an object ",
  "I felt confident using the tactile bracelet to locate and grasp an object ",
  "I waited for instructions before reaching to grasp an object "
)

# PC3: security, confidence, practice
confidence <- c(
  "I was in fear of hitting the shelf or objects during the task ",
  "I felt secure during the task ",
  "Mainly my intuition guided my hand movement during the task ",
  "I was able to develop a spatial understanding of the shelf ",
  "I could identify the vibration locations without much effort ",
  "The practice trials were sufficient to get comfortable with using the tactile feedback "
)

coded_data$PC1 <- coded_data$Question %in% usability
coded_data$PC2 <- coded_data$Question %in% task
coded_data$PC3 <- coded_data$Question %in% confidence
```

Coding direction

For negative questions we are changing the coding direction, such that a higher value consistently represents higher agreement with the underlying construct, e.g. "The intensity of vibration varied strongly" responses will be reversed in order. Note: Grasping anticipation during the task under the experiment design construct is a bad thing.

```
conditions <- coded_data$Question %in% c(
  "It was difficult for me to interpret the vibration cues from the tactile bracelet ",
  "The vibration from tactile bracelet felt uncomfortable on my hand ",
  "The intensity of vibration varied strongly ",
  "I was in fear of hitting the shelf or objects during the task ",
  "I was anticipating the grasping motion "
)

# change coding direction
coded_data$Response[conditions] <-
  ifelse(coded_data$Response[conditions] == 1, 5,
         ifelse(coded_data$Response[conditions] == 2, 4,
                ifelse(coded_data$Response[conditions] == 4, 2,
                       ifelse(coded_data$Response[conditions] == 5, 1, 3))))

# rename questions for easier interpretability
coded_data <- coded_data %>%
  mutate(Question = case_when(
    Question == "It was difficult for me to interpret the vibration cues from the tactile bracelet " ~ "
    Question == "The vibration from tactile bracelet felt uncomfortable on my hand " ~ "The vibration fe
    Question == "The intensity of vibration varied strongly " ~ "The intensity of vibration did not vary
    Question == "I was in fear of hitting the shelf or objects during the task " ~ "I was not in fear of
    Question == "I was anticipating the grasping motion " ~ "I was not anticipating the grasping motion
    TRUE ~ Question
  ))

#coded_data
```

```
pc1 <- coded_data %>% filter(PC1) %>% summarize(mean = mean(Response), sd=sd(Response))
pc2 <- coded_data %>% filter(PC2) %>% summarize(mean = mean(Response), sd=sd(Response))
pc3 <- coded_data %>% filter(PC3) %>% summarize(mean = mean(Response), sd=sd(Response))

construct_eval <- data.frame(mean=c(pc1[,1],pc2[,1],pc3[,1]), sd=c(pc1[,2],pc2[,2],pc3[,2]), Construct=
  ggplot(aes(x=Construct, y = mean)) +
  geom_bar(stat = "identity", position = "dodge", colour="#CC9900", fill="#FFCC66") +
  geom_errorbar(aes(ymin = mean - sd, ymax = mean + sd), width=0.2) +
  #geom_text(aes(label = round(mean, 2)), position = position_dodge(width = 1), vjust = 2, hjust=0.5) +
  labs(
    #title = "Mean participant evaluation per construct",
    x = NULL,
    y = "Mean response (Likert-scale) \n",
    ) +
  theme_linedraw() +
  scale_y_continuous(limits=c(0,6))

construct_eval
```




```
#ggsave(paste0(SAVE,"construct_eval.jpeg"), plot = construct_eval, dpi = 600)
```

Interpretation: Participants rated the usability of the bracelet lowest with a mean of 3.66 (sd = 1.32), most certainly because some participants had a hard time correctly interpreting the vibration signals as motors directly on a bone spread the signal across larger areas. Task design and the usage of the bracelet in the specific task was rated highest with 4.29 (sd = 0.88), indicating a generally good experimental design and adaptation to the bracelet. Confidence of using the bracelet was rated with 4.0 (sd = 1.21) suggesting that the idea of the bracelet and the usage itself are learnable relatively quickly. Overall, participants rated the whole experience relatively high which serves as confirmation for further developing the bracelet.

References

- Kording, K., Blohm, G., Schrater, P., & Kay, K. (2018). Appreciating diversity of goals in computational neuroscience. OSF Preprints.

- Norman, G. (2010). Likert scales, levels of measurement and the "laws" of statistics. Advances in health sciences education, 15(5), 625-632.

- Sullivan, G. M., & Artino, A. R., Jr (2013). Analyzing and interpreting data from likert-type scales. Journal of graduate medical education, 5(4), 541–542. https://doi.org/10.4300/JGME-5-4-18.
- de Winter, J.C.F., & Dodou, D. (2010), Five-Point Likert Items: t test versus Mann-Whitney-Wilcoxon, Practical Assessment, Research and Evaluation, 15(11).