ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Integrating peripheral visual perception with a curved perspective in an Oculus HMD

Semester Project

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Acknowledgment

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1 Introduction

Spherical projections techniques have the potential to increase the field of view in a virtual environment without introducing has many distortion as with a classical pinhole camera. Specifically in an environment explored with head mounted devices, the current state of the art of those device doesn't allow for a field of view as wide as the human eyes one. We try different methods of projection to expend the field of view that one gets in such an environment, and we try to estimate the advantages and drawbacks of such methods. We focus on our research on three area that should matter to the end user: the performance difference in realizing typical tasks, the well-being of a subject exploring this environment – we try to measure the discomfort that such techniques could introduce - and the feeling of embodiment in a virtual avatar.

2 Related Work

2.1 Spherical projection

Spherical projection as a replacement of the standard pinhole camera model, is a subject that has been largely investigated. Many different methods can be used to render an virtual scene with such a projection. We typically found three different methods: ray-tracing (Greene 1986), scene's vertices preprocessing (Oros 2002) and texturing a deformed mesh (Trapp 2008). As the first method is the best for minimizing artifacts and the general visual quality of the rendered image, it is also the most costly and does not take full advantage of the capabilities of modern hardware. The second method seems to be the best compromise between the cost and the quality of the rendered image, but is less portable as it requires modifying the standard projection via a vertex shader, it is thus more complex to integrate. Our choice will then be the third one, as it is easy to integrate within the classical rendering pipeline, particularly under Unity, the platform that we will use to design the virtual environment.

2.2 Tasks execution performance

The performance difference that a curved projection introduce while interacting with a virtual environment has also been studied (Ardouin, 2013). They found that navigating under a virtual scene with the goal of locating and collecting objects was improved by those methods. However, in their setup they focused on virtual environment navigation with a gamepad, displaying the virtual environment in a monitor. Here we focus on using curved projection under an immersive virtual reality setup, with a Head mounted display and motion capture sensors.

2.3 Cybersickness

As one of the main focus of this experiment is the feeling of embodiment in the virtual avatar, we have to take into account the potential sickness that such an environment could induce. The sickness induced by a virtual environment explored within a simulator or a head mounted display, is a topic that was also already extensively studied (Rebenitsch, 2014). Across different research, we noted that a questionnaire to assess the adverse effects of a given scene, the Simulator Sickness Questionnaire (SSQ, see Appendix A) is the benchmark in this field. (Kennedy, 1993). We will use this method, because it provides a good estimation and because since it is widely used it could allow the reader to compare the score with other studies. The method relies on a questionnaire that the participant answer right after the immersion.

3 Implementation

3.1 Spherical projection characteristic, design and implementation

As we found in the related papers, the easiest way to integrate spherical projection techniques relies on the classical rendering pipeline. As one of the goal of this project is to implement the experiment scene within Unity, this might be the most affordable possibility. We also found that another experiment using this technique was done under Unity by using predefined meshes. The goal of this project was to project images over spherical surfaces (Bourke, 2008). We followed that idea, dynamically creating the meshes according to projection techniques and parameters.

The spherical projection method that we use relies on the classical pipeline. That means that we have to use standard cameras. In other words, we have to transform images acquired with perspective projection into a spherical projection. To do so, the method consists in using six cameras to get a full panoramic view of the scene from a point: a cube map. The second problem then consists in projecting that cube to a Sphere and then to project that Sphere to a distorted planar mesh, which we can display.

For that we have two options, to work on the fragments of the six previously acquired textures, or design a mesh that maps a cube to a plane – as aforementioned – and then texture that plane and render it. As the method has to be reusable and portable, working with a mesh is the only solution that allows us not to introduce new shaders into the program.

Mapping the mesh of a cube to a sphere is pretty straightforward, as it consists in transforming each of its vertices into unit vectors.

Mapping a sphere to a plane is the hardest problem as there is no straightforward solution. The projection will necessarily introduce distortions to the mesh. Fortunately, this in itself is an area of research: cartography, map projection. We will use results from this field for this project.

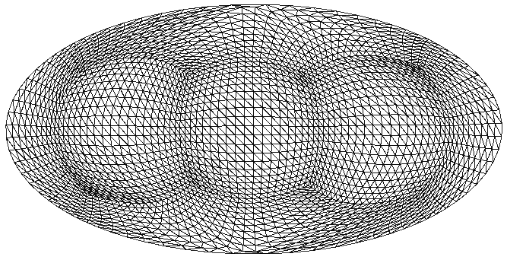

Figure 1: Cube projected to a sphere and then to a plane using Hammer projection

The goal of cartography is to project a representation of Earth into a plane, which is in all point similar to what we are doing. It has been proven that a sphere cannot be mapped to a plane without adding distortions, but as different projection techniques exist, they can maintain certain properties of the geometrical object.
A mapping that preserve

- direction (a straight line from one or two given point remain straight in the projection) is called *azimuthal*.
- angles (a given angle – an infinitesimal sphere – at any point on the mapping is preserved) is called *conformal*
- area (any measure of area is proportionally correct) is called *equal-area*
- distance (any measure of distance from one or two given point is proportionally correct) is called *equidistant*

A mapping that does not preserve metric properties but instead focus on keeping balance between the different distortions added is called *compromise* (Wikipedia, Map projection).

For this experiment, as those mathematical properties don't tell much by themselves about how would a given projection be perceived and felt by the users, we will try different projections.

The first criteria of selection that we used to filter projections, before the implementation, was the consistence of the curved projection as compared to a regular perspective projection. The planar mesh produced has to be squared, rectangular, spherical or elliptical, but should not introduce sharp edges at it's border or blank areas in the center of the mapping.
The second criteria is that it has to represent the full sphere.
And the third, which is subjective, it should not introduce too many visual distortions, it should produce a visually harmonious result.

We implemented nine of them: Lambert (Equal-Area), Bottomley (Equal-area), Bonne (Equal-area), VanDerGrinten (Compromise), Equirectangular (Equidistant), Mercator (Conformal), EckertIV (Equal-area), Hammer (Equal-area), FishEye (Equidistant).

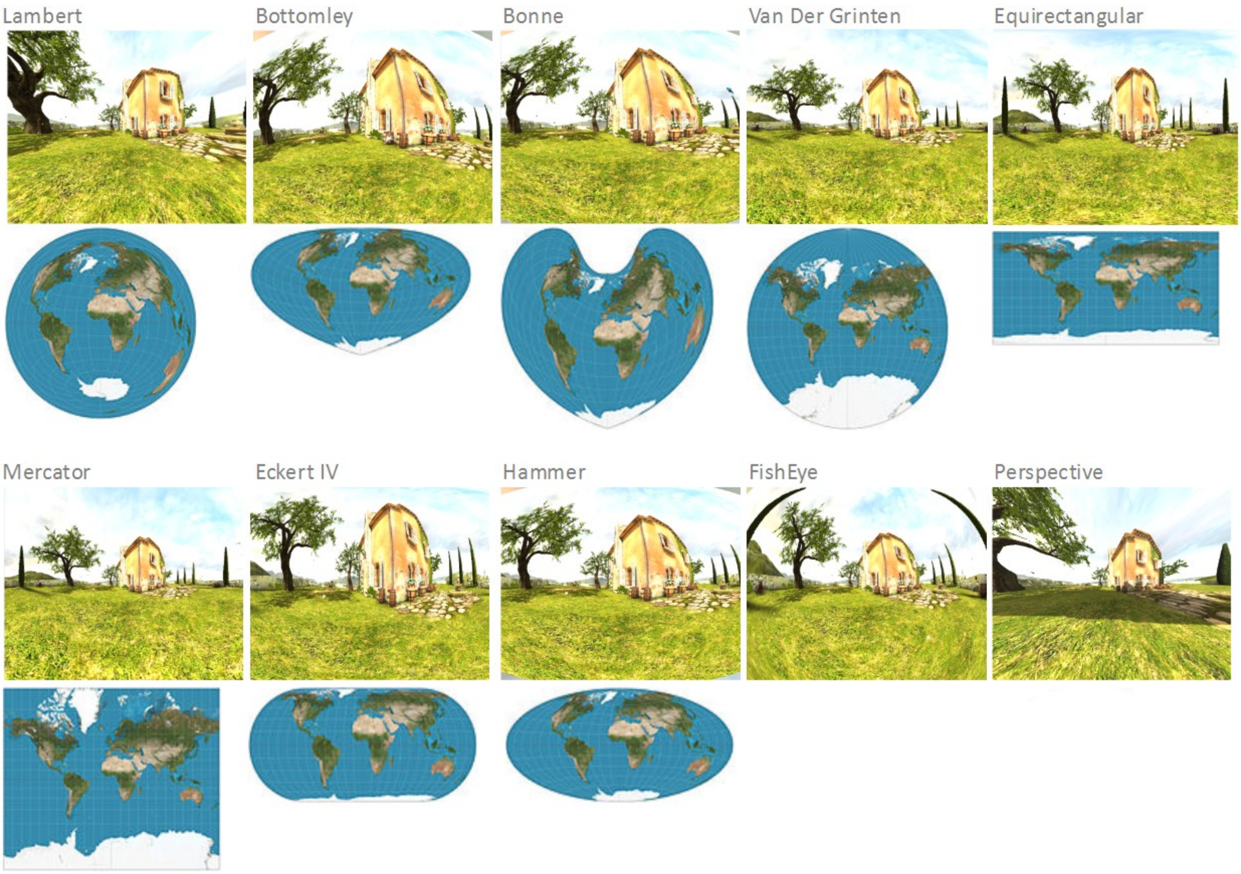

Figure 2: Different projection techniques, applied to represent the Earth and a virtual scene

We also wrote scripts to dynamically produce such a camera for each eye; to produce the cube map and texture the meshes; to integrate it with the Oculus Rift plugin for Unity; to be able to parametrize the field of view that the projection provides, the number of vertices that the mesh is made of, and the size of the six textures.

After multiple trials we also tried to implement our own projection techniques: a mix between perspective and fishEye; a mix between perspective and Hammer; and a mix between perspective and Bottomley. The goal of those projections was to preserve a perspective representation of the world at the center of the image (having no distortion in that zone), and keeping the extended field of view that the spherical projection provides outside. We designed them by computing for a given vertex on the final planar mesh, its distance from the center. We would then reassign the position of the vertex proportionally to that distance. Near the center the vertex position would be closer to the one it had on the initial cube, and along that distance, while approaching to a threshold, it would get closer to its default position on the final mesh. That way the mesh produced has a more regular grid at the center. (See figure 3 and 4)

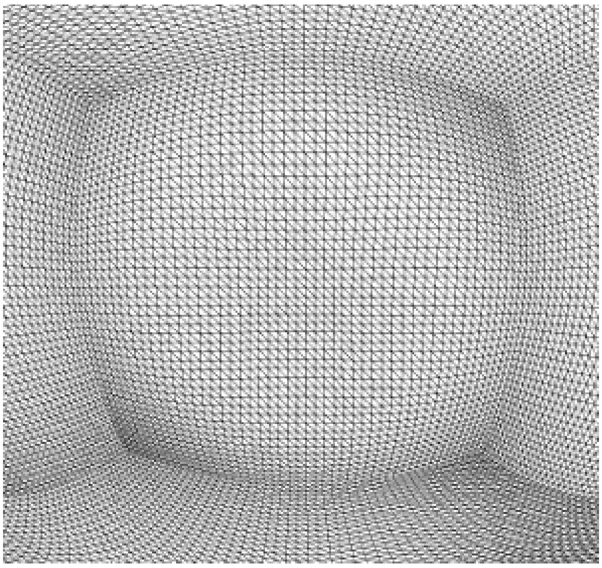

Figure 3: mixed projection, perspective at the center, Hammer around

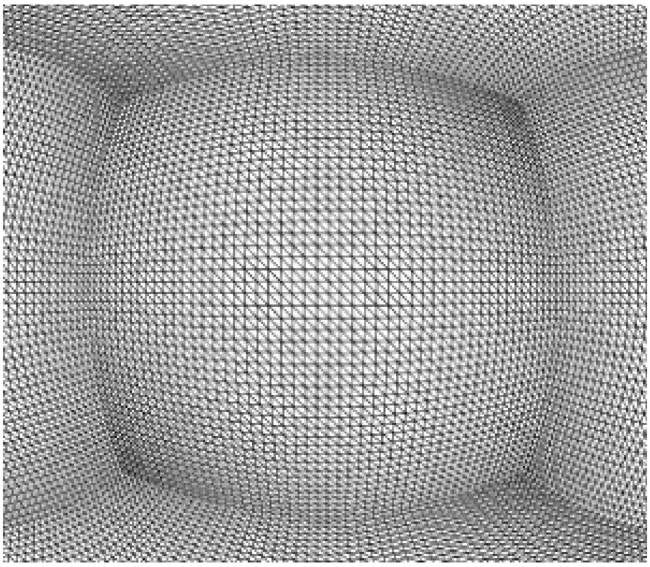

Figure 4: Hammer projection

The problem that arose with that technique is that in spite of using a soft merging function along the radius, the transition border remained visible in the sense that in this zone (a circle around the center) transition artifacts and strong distortion were visible. Such projections could still be used in an environment where the precision at the center of the screen is really important and the realism of the scene is less. But in our case we choose to not test those projections during the experiment.

Finally, we tried internally those nine projections extensively and choose two from them to be tested on the subjects. We choose one representative of the equal-area type of projection, Hammer, because it is the one that introduce the less distortion in the south pole region (the body region of the image), and thus could allow a more immersive experience in the sense of the embodiment feeling. And one representative of the equidistant type of projection, equirectangular because it introduced less distortion in the shelves region, and thus shouldn't disrupt the task to be accomplished.

3.2 Experiment design

A pilot experiment was conducted with 6 volunteers aged from 17 to 25 years old, five of them masculine, all with prior video gaming experience and all with few or no experience of head mounted display (the exact characterization of each participant can be found in the Appendix B). The experiment followed a within subject design with Projection as a three levels factor that could be either: Perspective, Equirectangular or Hammer. The exposition order to the 3 projections was counterbalanced.

The subject seated on a chair at the center of the position tracking space. He wore an Oculus Drift DK2 head mounted display (HMD). A Phasespace Impulse 2 was used to track four LED markers, which were attached to hands and elbows of the subject. Additionally, two Playstation Move controllers were used to track hands orientation and allow for input with a trigger button.

3.3 Procedure

The subjects were asked to fill in a characterization questionnaire, and were provided with oral instructions and explanations of the experiment.

The participants had to take three blocks, one for each of the three different selected projections.

A block consisted of repeating the task of selecting a ball, moving and releasing it in a docking position 24 times. Four times for each of the possible six positions at which the ball could appear. The docking target had a constant position for all balls. The order in which the tennis balls were shown to the subject was randomized, with the constraint that they would never appear in the same location in sequence.

They did the first block with the first projection, then received three questionnaires to fill, the SSQ, the embodiment questionnaire and the virtual scene sizes and distance estimation questionnaire (Appendix A). They then did a second block with the next projection, and answered the SSQ and embodiment questionnaires again. They finally did the third block with the last projection, and answered the SSQ and embodiment questionnaire one last time. The order in which they experienced the different projections was counterbalanced.

3.4 Virtual environment

The virtual avatar sits on a chair, as in the reality. Two shelves are surrounding him. One at his left and one at his right. Both shelves are identical, they have two racking compartments one a bit below the shoulder of the avatar and one a little bit above. A wall is located in front of the avatar. The goal of the experiment is to move tennis balls inside a target. The tennis balls appear on the shelves one after the other at six predefined positions. One on the top rack of each shelf, and two on the bottom rack of each shelf (Figure 5). The participants were asked their height at the beginning of the experiment. While they were answering the first questionnaire, the experimenter parametrized the virtual avatar size to match the participant's one.

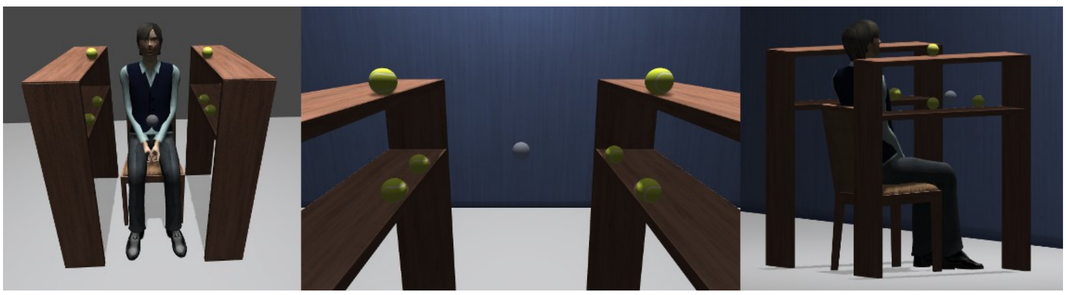

Figure 5: Frontal, first person and isometric view of the scene

3.5 Motion controllers

The subject could control the left and right arm of the virtual body. An inverse kinematics algorithm was used to enforce the symmetry between the location of the real and virtual hand. The algorithm is based on six degrees of freedom, describing the real hands pose (the Phasespace markers provided the position and the Playstation move controllers the orientation) and the elbows position.

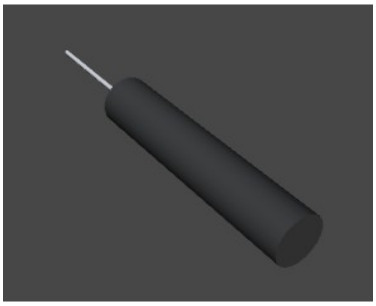

Figure 6: Virtual representation of the PS Move, with the selection pinpoint

3.6 Tasks to be completed

The subjects could interact with the tennis ball by selecting and moving them with the Playstation move controller. More specifically, when the pinpoint located at the end of the virtual controller was colliding with a tennis ball, the subject could press and hold the trigger button to select and hold the ball, moving the controller would move the tennis ball accordingly.

The user had to select the ball, move and release it inside a docking target located in front of him. The tennis ball then disappeared and another one appeared on the shelves. If the subject released the tennis ball before reaching the docking target, the tennis ball disappeared and was moved to the end of the trials queue, so that the subject had to try to do it again at the end of the block.

3.7 Task measurement and calculations

We wrote scripts to log the whole experiment. Specifically, we logged the position and rotation of all the moving body parts; the positions of the tennis balls; the beginning and end of each selection; the success or failure at the end of a selection and the collisions between all the elements.

From those measures we were able to calculate for each block, the number of failures, the quantity of head movements (the summed angular distance between the two orientations of successive log frames). For each block and for each successfully dropped ball: the time from the selection to the release, the time to locate the next ball (from the previous release to the selection), the direct distance from the point of selection and the point of release, the traveled distance

from the point of selection to the point of release (the summed difference of positions between each log frame), the average speed of the ball (the traveled distance over the time), the space efficiency (the ratio between the direct distance and the traveled distance) and the precision (the distance from the center of the target at which the ball was released).
Moreover, only measuring their performance in the experiment would lack a qualitative estimation of the different projections. Thus we also adopted three questionnaires to assess: cybersickness, with the Simulation Sickness Questionnaire (SSQ); reported embodiment, with a body ownership and agency questionnaire; and perception of the environment structures, with the estimation of distance and sizes of objects, such as the shelves. (Appendix A). To prevent learning bias, the latter was only applied once, by the end of the first block.

4 Hypotheses

We hypothesized that the projection used might influence those results.

H1: using a spherical projection might decrease the quantity of head movements, as the field of view is bigger, the user might rotate his head with a smaller amplitude to locate the target.

H2: using a spherical projection might decrease the space efficiency, as the projection is curved, the user might move the ball along a curve instead of a straight line.

H3: using a spherical projection might decrease the precision, as the field of view is bigger the angular size of the virtual objects is reduced, making it harder to reach precisely.

H4: using a spherical projection might decrease the time to locate and move the target ball, as the field of view is bigger, the ball should be accessible quicker. If so we expect that the time to select the 4 targets in the lateral of the subject to be smaller for the spherical projection as compared to perspective.

H5: using a spherical projection might affect the score on the SSQ questionnaire, as the projection is curved and add distortions, the user might feel more cybersickness after the experiment.

H6: As the spherical projection will show the virtual body more often to the subject than perspective, we expect stronger ownership response on the embodiment questionnaire for spherical projection.

5 Results and discussions

Statistical significance analysis was carried with one-sided paired t-test for performance data, and Wilcoxon signed-rank test for questionnaire data. Results are presented according to the aforementioned hypotheses.

H1: This number is the summation of the angular distance between the two head orientation in each successive frame of the log, it is calculated for each ball selection and then averaged for the block. It thus represent the mean angular distance in radians that the head traveled between two ball selection. We found there is a significant difference at 5% for mean head movement quantity comparing perspective to Hammer and perspective to equirectangular. Specifically, significantly more head turns for perspective as compared to equirectangular, $p < 0.001$ significantly more head turns for perspective as compared to Hammer, $p < 0.016$ and significantly less head turns for equirectangular as compared to Hammer, $p < 0.042$.

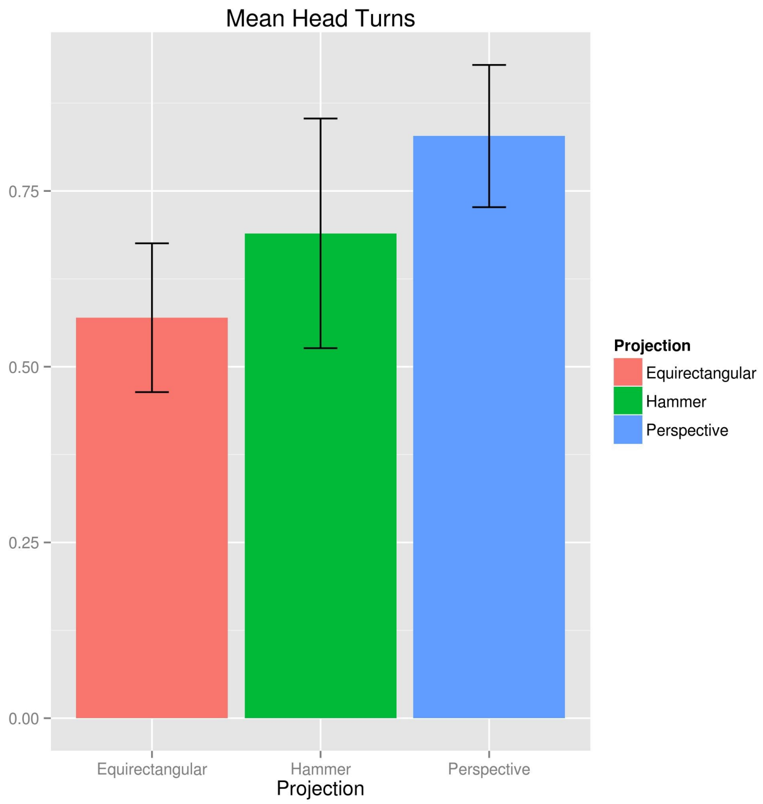

Figure 7: Mean head turn quantity per ball (rad)

H2: This number is the ratio between the distance that the ball actually traveled between its selection and release divided by the distance of the shortest path between the two (the direct distance). It represent the directness of the path. For instance 1.0 would represent a perfectly straight path and 2 represent a path that is twice longer than the shortest path. We found no significant difference for this ratio between any of the projections. The type of projection does not seem to influence the directness of the path that the ball follows from its selection to its release.

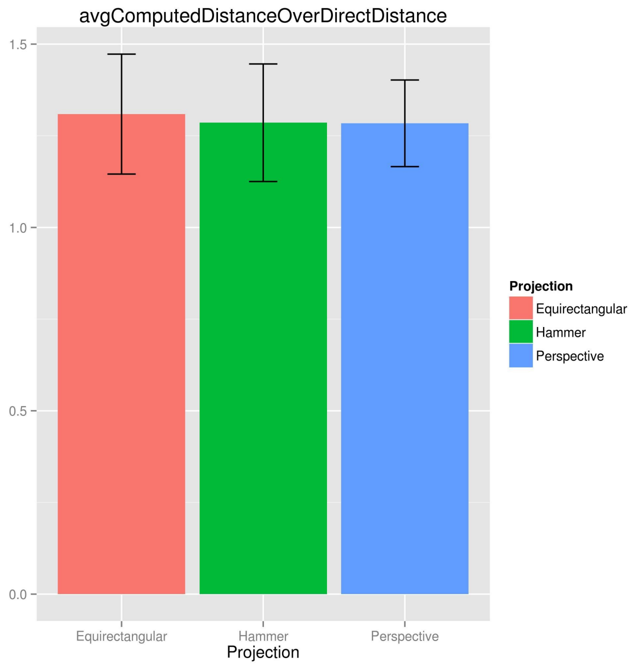

Figure 8: Ratio, traveled distance over direct distance

H3: The docking error stands for the distance in cm from the docking target at which the ball is released. As the only condition for a drop to be successful is that the ball and the target collide. It is thus bounded between 0 and the radius of the target plus the radius of the ball. We found significantly less docking error for perspective as compared to hammer, $p < 0.024$. Interestingly, no significant difference were found between equirectangular and perspective. It might come from its equidistant mathematical property. As the distance between meridians are constant and proportional within this projection it probably introduced less stereoscopy distortions and thus less incertitude about the ball position along the z-axis.
It is also interesting to report that one of the subject had a difficulty completing the task within the equirectangular and Hammer projections, with 20 failures (ball released before reaching the docking target) for the first, 35 failures for the second, and only one for perspective. The failed trials were replaced at the end of the trial queue, that way every block had exactly 24 success. The other

subjects were not affected.

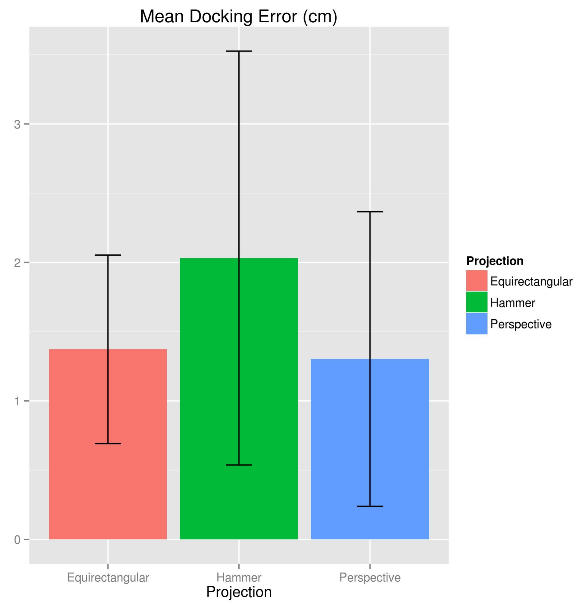

Figure 9: Docking error, distance from docking target at release position (cm)

H4: We found no significant differences at 5% between any of the projections neither comparing the location time nor the moving time. We will however comment on their mean differences under the assumptions that it could indicate a potential significant difference in the case of a bigger subject sample.
The mean time to move the ball (measured from it's selection to it's release) seems to be independent of its position (lateral or frontal). In all cases the highest mean time is equirectangular, then Hammer and the smaller is perspective.
The mean time to locate the ball however (the time from the previous ball release to the current ball selection) seems to show that the subjects performed better within the Hammer projection than the perspective projection for all ball positions. (On the next figure, where MT stands for mean time, and is the moving time, while MTL stands for mean time location, and is the location time).
H5: We find no significant difference at 5% between the total SSQ

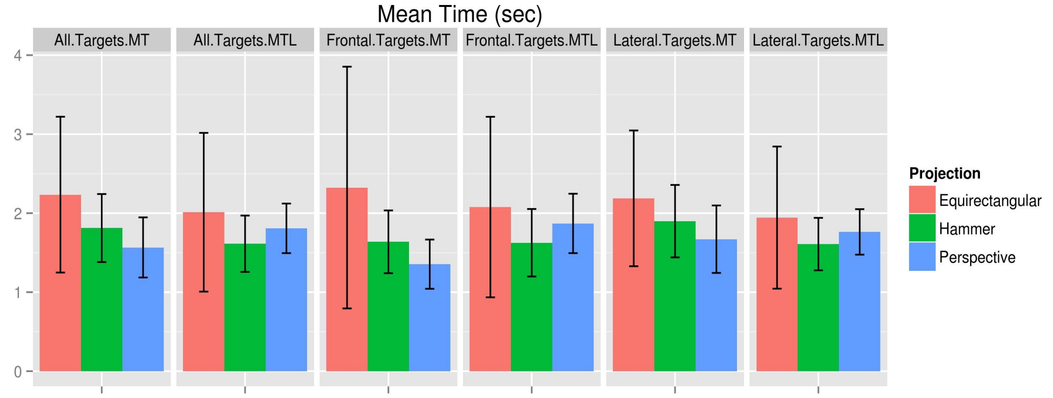

Figure 10: Mean times for categories of target. MT stands for mean time, and is the moving time (from selection to release), while MTL stands for mean time location, and is the location time (from previous release to selection)

score comparing the different projection. Possibly because the sample size is too small or because of the characteristic of the sample, all subjects were under 25 years old and used to video games. Another explanation could be the immersion time, as it was rather small (between 2 to 10min per block), it could be too short to experience adverse effects.

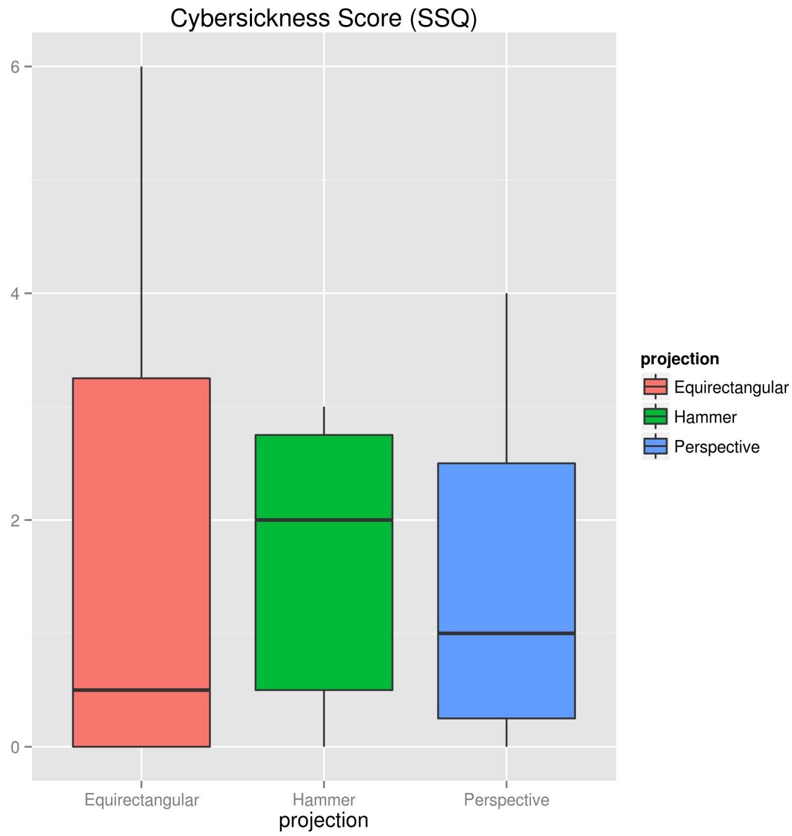

Figure 11: SSQ Score, sum of all entries (Annexe A).

H6: The body agency and ownership scores refer to the embodiment questionnaire (Appendix A). Each score is a summation of specific question, with the negative question inverted. Agency refers to questions 2, 4 and 6 while ownership refers to questions 7, 8, 9, 10. The two additional questions (3 and 5) are control questions. We found no significant difference in body agency score, which suggests that the distortion added by the curved projections do not affect the perception and attribution of self generated movements. However, the sample size is too small to draw string conclusions.

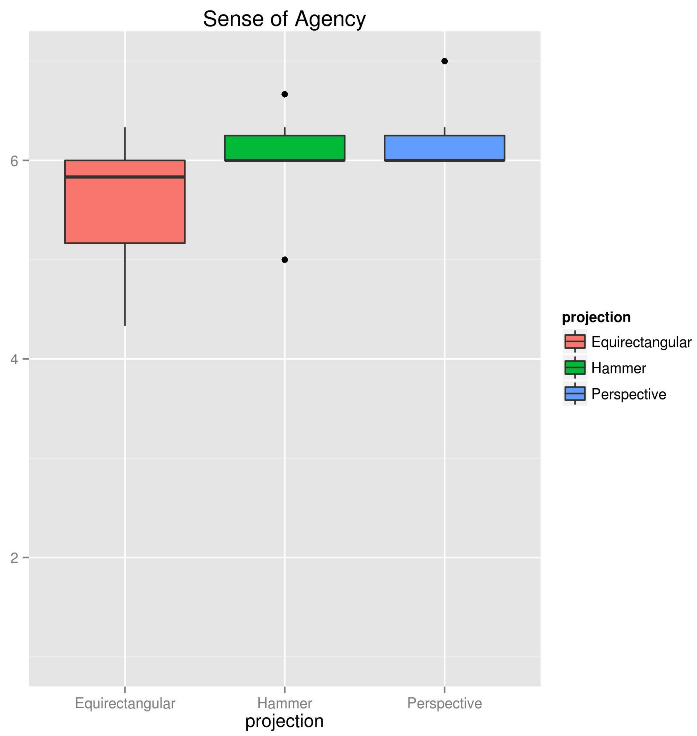

Figure 12: Sense of agency, embodiment questionnaire (Annexe A), question 2,4 and 6

Moreover, no significant difference at 5% was found for ownership, However, the median for Hammer projection was the highest one, which suggests that the curved projection does not negatively impact Ownership.

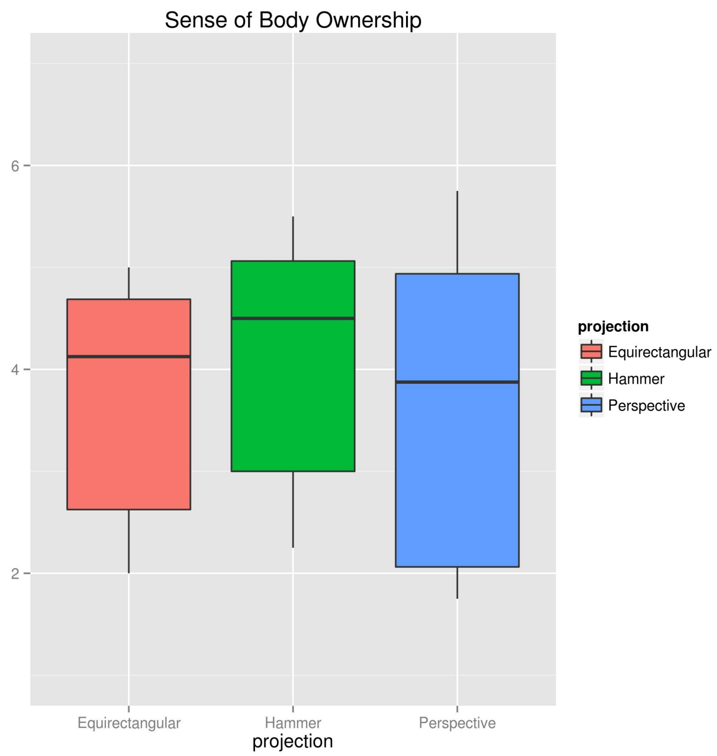

Figure 2: Sense of body ownership, embodiment questionnaire (Appendix A), questions 7, 8, 9 and 10

We did, however, find that the difference between Equirectangular and Hammer was close to the significance threshold (at 5.3%) when comparing body ownership score. As the median are still very close to each other, the score can range from 1 to 7 and the interquartile range of both are pretty high, we might want to be extremely careful about the importance of this result. It might nonetheless, indicate a significant difference in the case of a bigger sample. It also seems to be consistent with the mathematical properties of both projections, as the equirectangular projection adds a lot of distortions in the poles regions (the south pole represent the body region) while Hammer proportionally represent any area measurement. This is another interesting point that could be addressed in a more complete experiment.

Possible bias of the experiment.
As this is a semester project the sample of the subjects that took the experiment might not be representative of the general population. Multiple factors could bias the experiment. Specifically the sample size: as only six participants took the experiment the sample is rather small and some results might not be conclusive because of this. The subject characterization: no subject was aged over 25 years old, only one female participant took the experiment, only one participant was not from the EPFL, they all had interests in virtual environments, they were all from the entourage of the experimenter (family, friend or friend of friend), and they were not paid (might introduce some cognitive dissonance, induced-compliance paradigm).
All those factors could bias the results that the participant provided to the questionnaires as they might be more positive about the experiment than a neutral and representative sample.
Nevertheless, the performance part of the experiment was probably not affected as the results derive from measures and could hardly be biased by the participant psychology.

6 Conclusion

As the results show, this experiment does not allow us to derive strong conclusions. However, it gives us valuable insight about situations in which their use might improve the user experiment.
In particular the equirectangular projection might be useful when the user needs to have a bigger field of view on the horizontal axis, for instance, to locate objects or enemies in the case of a game, while preserving a good estimation of the position of an object along the z-axis at the center of the screen. It have the advantage to limit the number of head movement for doing so. It does however not significantly improve speed in doing such tasks so the goal of it's usage would mainly be the user comfort.
Hammer on the other hand is inferior when it comes to precision and other tasks that require a good depth awareness. It does however seems to improve the virtual body ownership and embodiment feeling when compared to equirectangular. It also seems to increase the speed of visual searching and selecting objects. It also reduce the quantity of head movement, but in a lesser extent than equirectangular. It might be useful for situation in which a good body awareness is needed, for instance in some sport simulations.

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8 Appendix
A Questionnaires

No________________ Date_______________________

SIMULATOR SICKNESS QUESTIONNAIRE
Kennedy, Lane, Berbaum, & Lilienthal (1993)***

Instructions : Circle how much each symptom below is affecting you right now.

1. General discomfort	None	Slight	Moderate	Severe
2. Fatigue	None	Slight	Moderate	Severe
3. Headache	None	Slight	Moderate	Severe
4. Eye strain	None	Slight	Moderate	Severe
5. Difficulty focusing	None	Slight	Moderate	Severe
6. Salivation increasing	None	Slight	Moderate	Severe
7. Sweating	None	Slight	Moderate	Severe
8. Nausea	None	Slight	Moderate	Severe
9. Difficulty concentrating	None	Slight	Moderate	Severe
10. « Fullness of the Head »	None	Slight	Moderate	Severe
11. Blurred vision	None	Slight	Moderate	Severe
12. Dizziness with eyes open	None	Slight	Moderate	Severe
13. Dizziness with eyes closed	None	Slight	Moderate	Severe
14. *Vertigo	None	Slight	Moderate	Severe
15. **Stomach awareness	None	Slight	Moderate	Severe
16. Burping	None	Slight	Moderate	Severe

* Vertigo is experienced as loss of orientation with respect to vertical upright.

** Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

Last version : March 2013

***Original version : Kennedy, R.S., Lane, N.E., Berbaum, K.S., & Lilienthal, M.G. (1993). Simulator Sickness Questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology, 3*(3), 203-220.

Embodiment questionnaire

1. **Subject ID**

....

Read carefully

(Mark your answer with a cross in the scale between "strongly disagree" and "strongly agree")

During the last session there were times when…

2. **…it felt like the body I was seeing was out of my control** *
Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

3. **…it felt as if I had more than one body** *
Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

4. **…it felt like I could move the body I was seeing as I wanted** *
Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

5. **…it felt as if my real body was turning virtual** *
Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	⬭	⬭	⬭	⬭	⬭	⬭	⬭	Strongly Agree

6. **...it felt like I was in control of the body I was seeing** *

Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

7. **... I felt as if I were wearing the clothes I was seeing, rather than my actual clothes** *

Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

8. **... it felt as if I could really touch the shelves I was seeing** *

Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

9. **...it felt that the body I was seeing was not my body** *

Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

10. **...It felt that the body I was seeing was my own body** *

Une seule réponse possible.

	1	2	3	4	5	6	7	
Strongly Disagree	◯	◯	◯	◯	◯	◯	◯	Strongly Agree

Characterization questionnaire

Pre experiment

*Obligatoire

1. **Identifier (filled by the experimenter)** *

2. **Height** *

3. **Weight** *

4. **Age** *

5. **How often do you participate on experiments using Virtual Reality equipments?** *
   e.g. experiments in other labs of the university.
   Une seule réponse possible.
   - Never participated of an experiment
   - A few times
   - Every month
   - Every week
   - Every day

6. **How often do you use head mounted displays?** *
   Une seule réponse possible.
   - Never used
   - A few times
   - Every month
   - Every week
   - Every day

7. **How often do you play video games?** *
Une seule réponse possible.

- Never played
- A few times
- Every month
- Every week
- Every day

8. **How often do use the Microsoft Kinect, Nintendo Wii or Playstation move?** *
Une seule réponse possible.

- Never used
- A few times
- Every month
- Every week
- Every day

9. **Hand of preference** *
usually, the hand you write with
Une seule réponse possible.

- Left hand
- Right hand

10. **Area of expertise/study/work/interest**
e.g. computer science, math, sales, mechanical engineering etc. (only the main one)

....

B Results

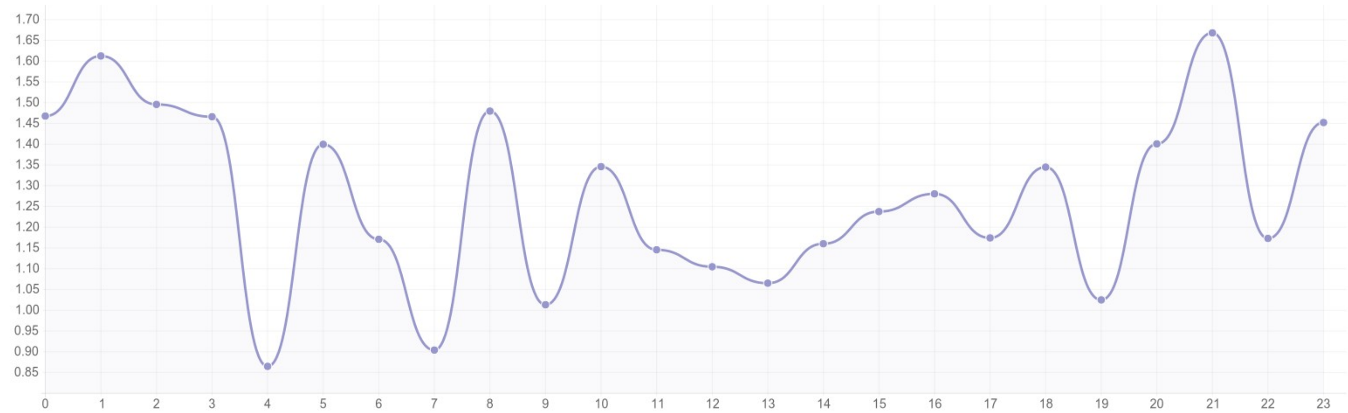
B1 Characterization

#	height	weight	age	male	How often experiment virtual	How often head mounted	How often video game	How often controller	Right handed	expertiseArea
1	182	75	25	1	0	0	3	1	1	Communication Systems - music
2	181	73	23	0	0	0	1	1	0	Computer Science – Communication Systems
3	177	88	23	1	0	0	2	1	1	Math
4	185	70	17	1	0	1	3	1	1	High School
5	180	65	23	1	0	0	2	0	0	Computer Science
6	179	74	23	1	0	0	3	3	0	Computer Science

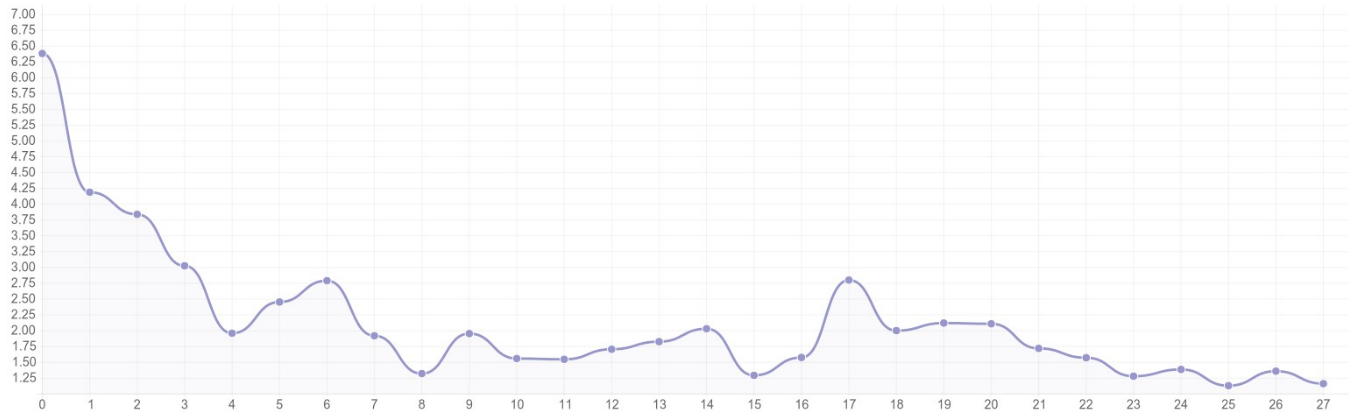
B2 Typical block charts

For each evaluated parameter we provide an example of it's evolution during one block. Every example are from the first trial of the first subject.

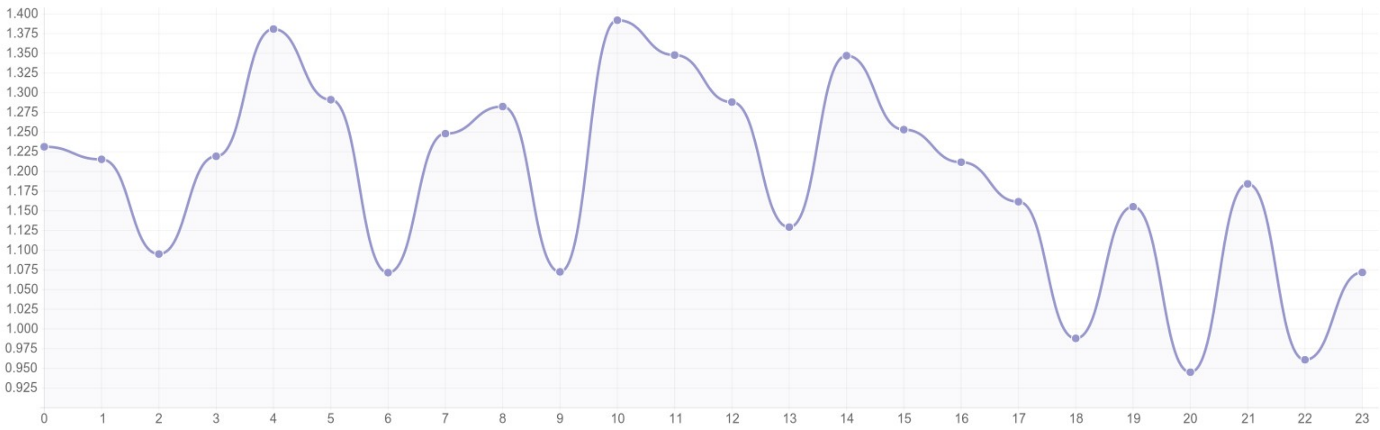
Ball Time (from selection to release)



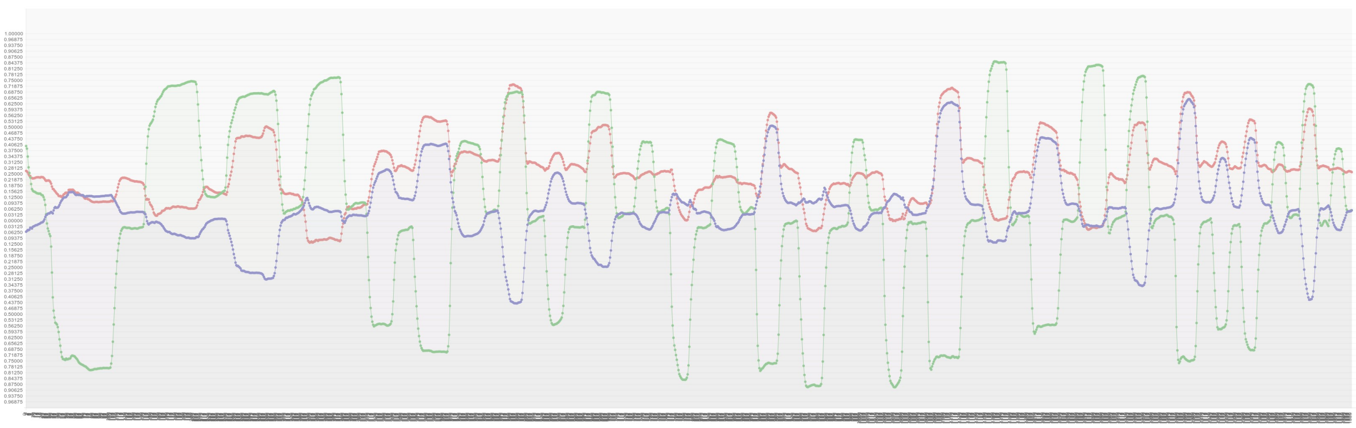
Ball location time



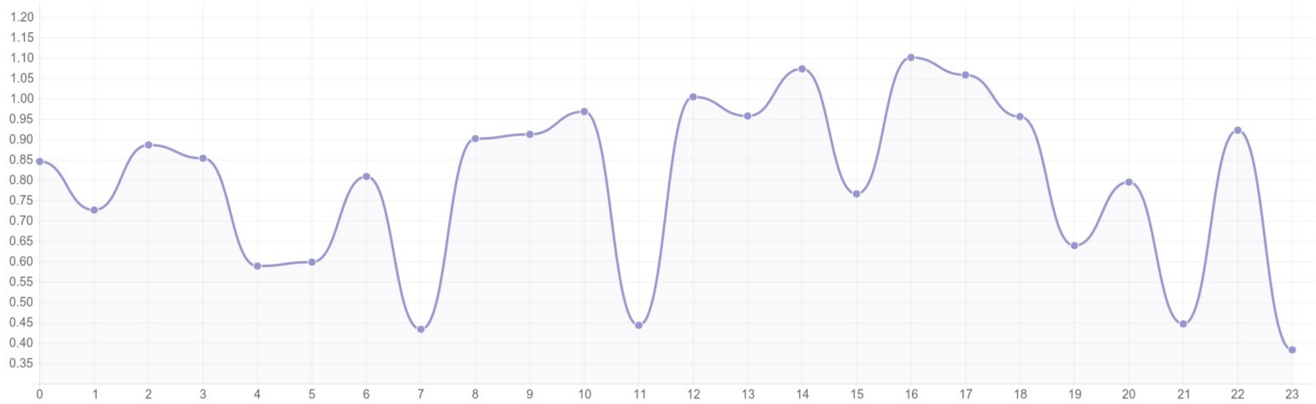
Space efficiency (traveled distance over direct distance)



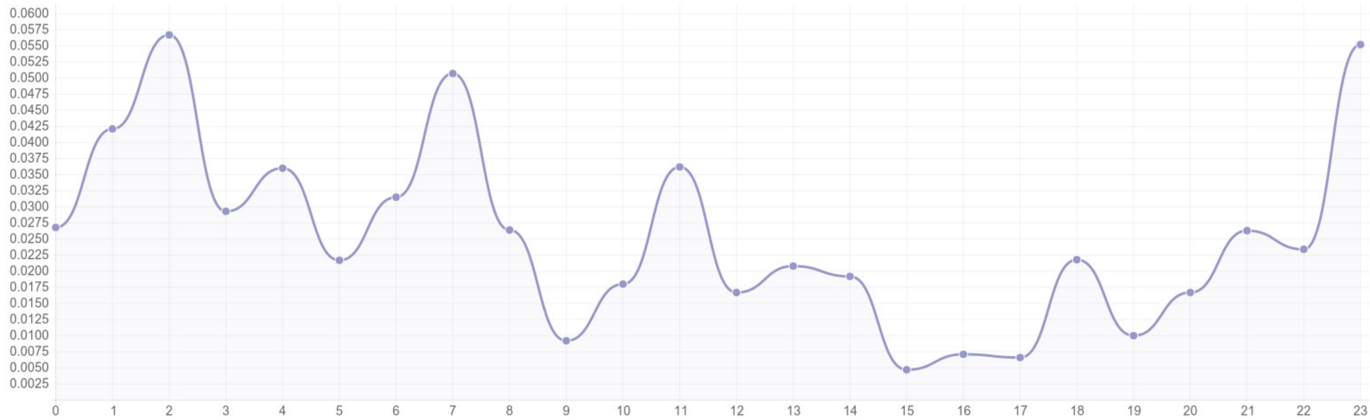
Head movements (x-axis, y-axis, z-axis)



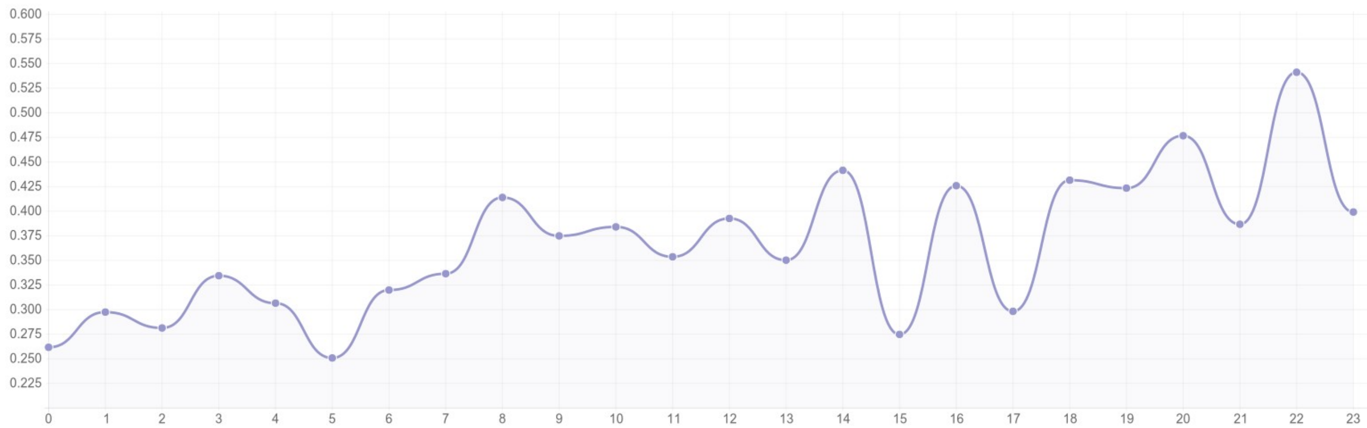
Head movement quantity (summed difference between each frame, for each ball)



Docking Error (distance from the docking target when released)



Mean speed (traveled distance over time)

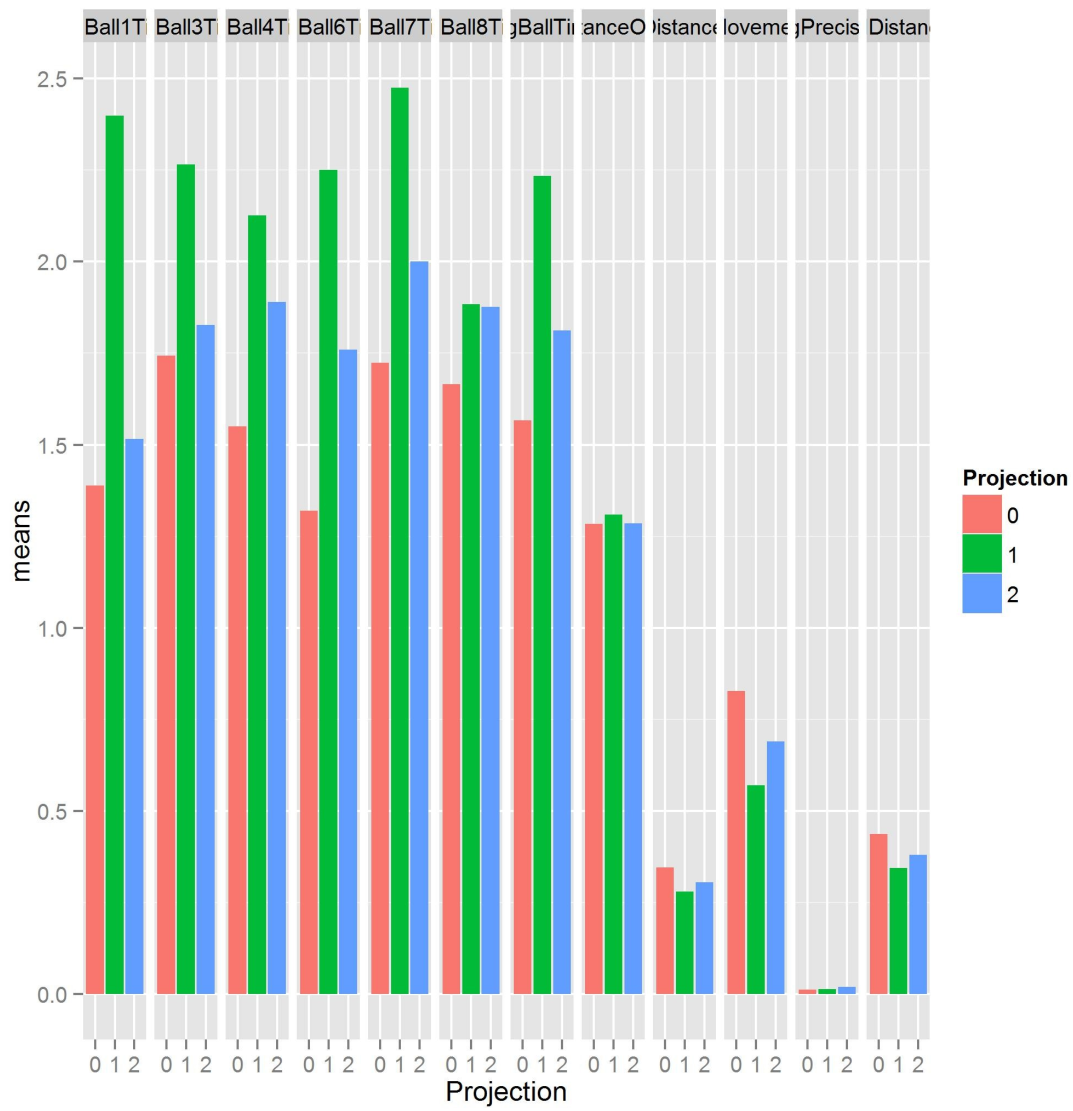


B3 Statistical charts

All parameters mean per projection type, 0 stands for perspective, 1 stands for equirectangular and 2 for Hammer

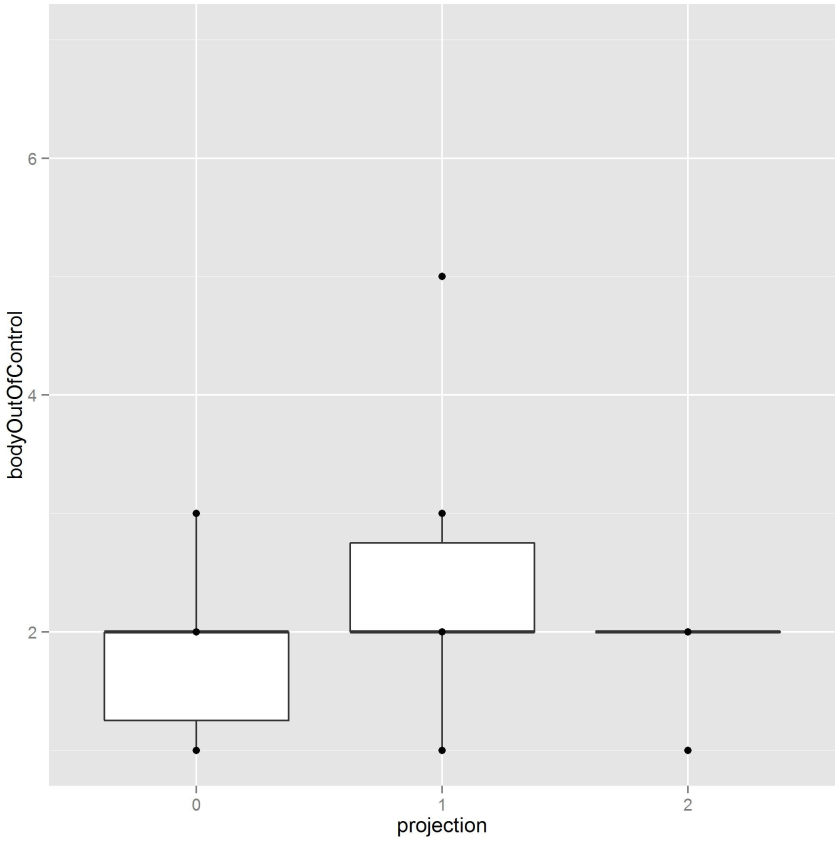
From left to right:

1: Mean moving time for right-bottom-front ball
2: Mean moving time for right-top-rear ball
3: Mean moving time for right-bottom-rear ball
4: Mean moving time for left-bottom-front ball
5: Mean moving time for left-top-rear ball
6: Mean moving time for left-bottom-rear ball
7: Mean moving time for all ball
8: Mean direct distance over time
9: Mean traveled distance over time
10: Mean Traveled disance over direct distance
11: Docking error (cm)
12: Summed Head movement quantity

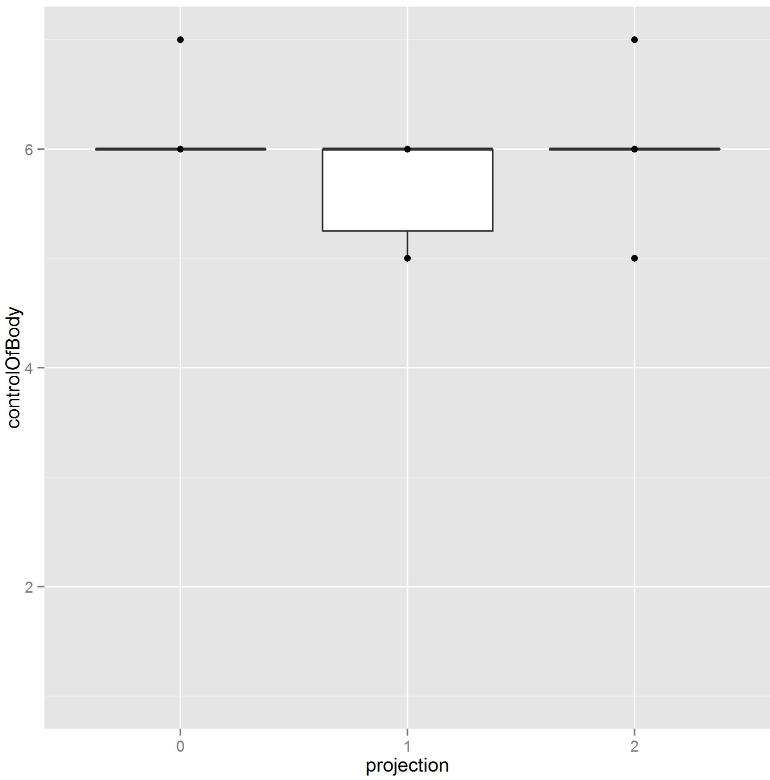


Embodiment questionnaire:

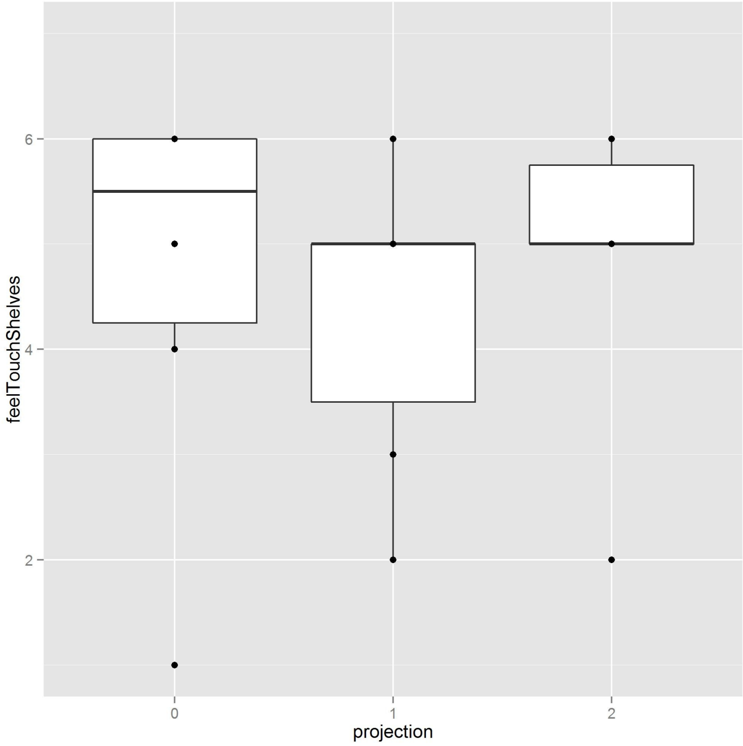
Body out of control



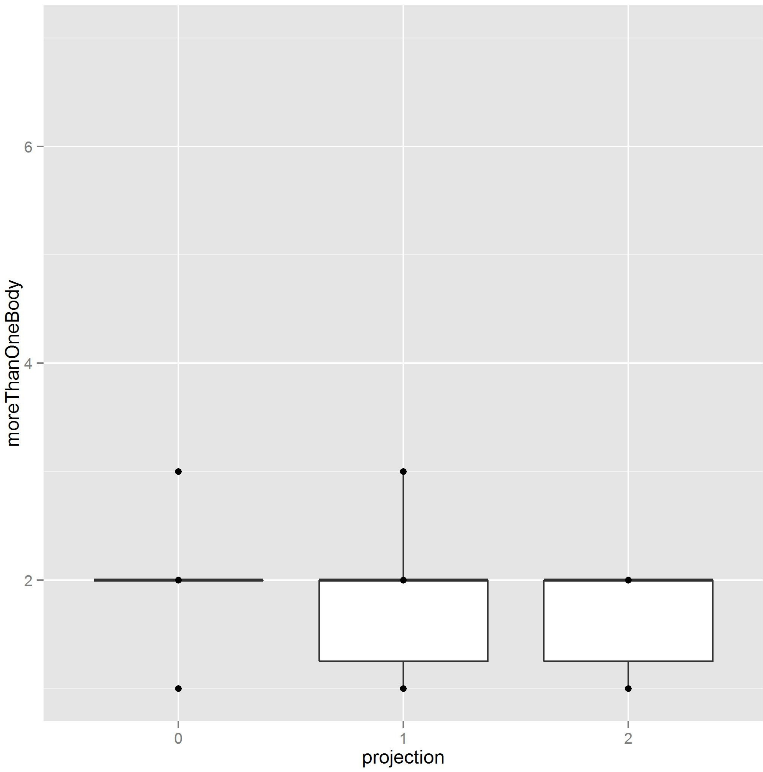
Control of body



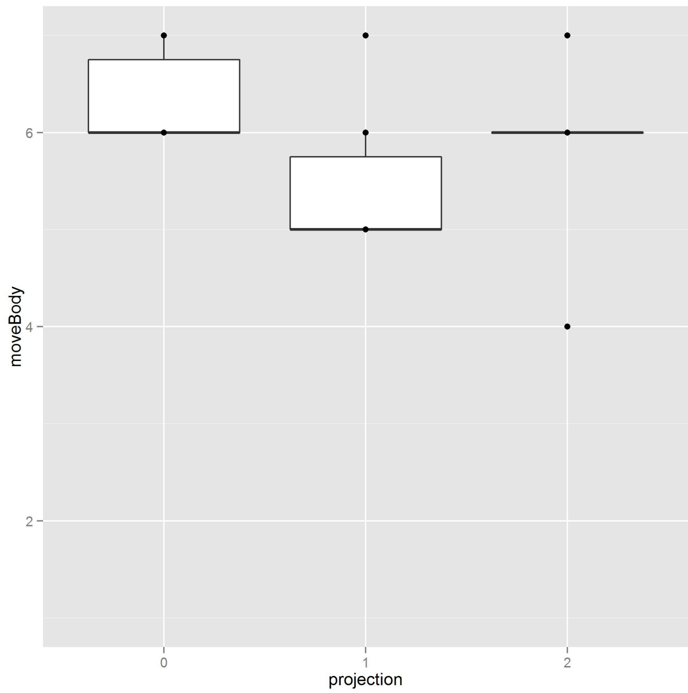
Feeling of being able to touch the shelves



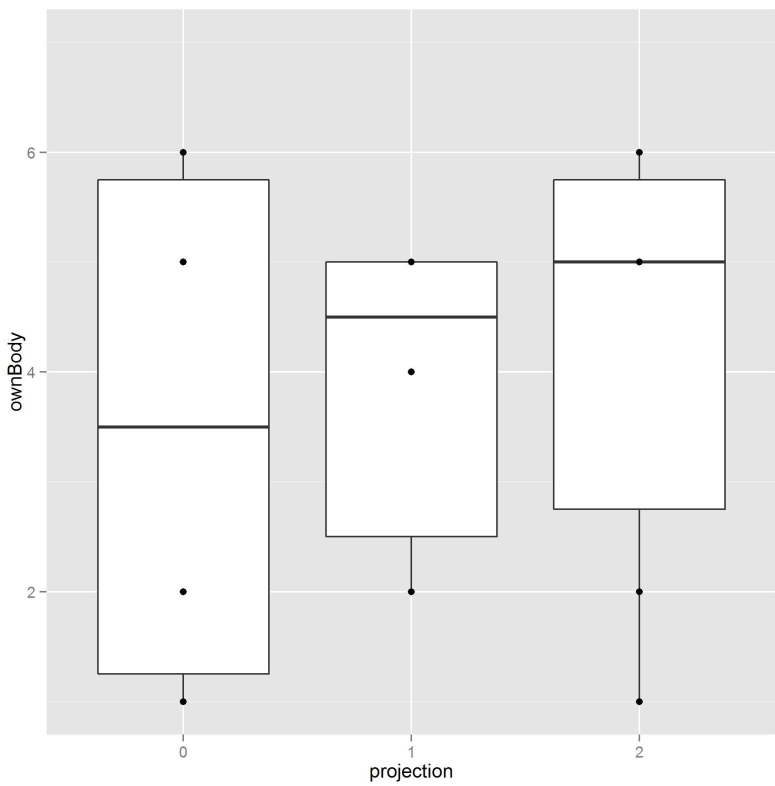
Feeling of having more than one body



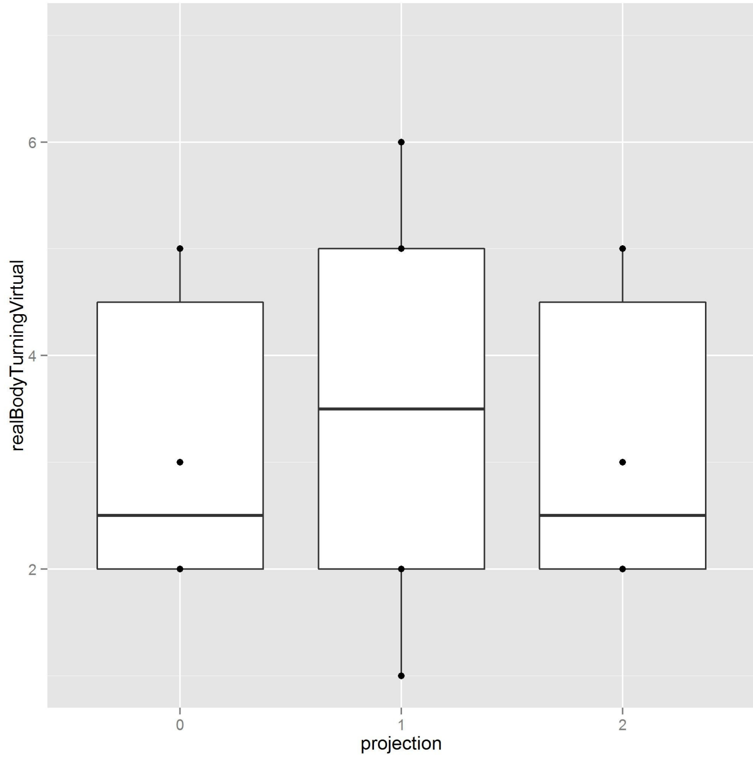
Feeling of being able to move its virtual body



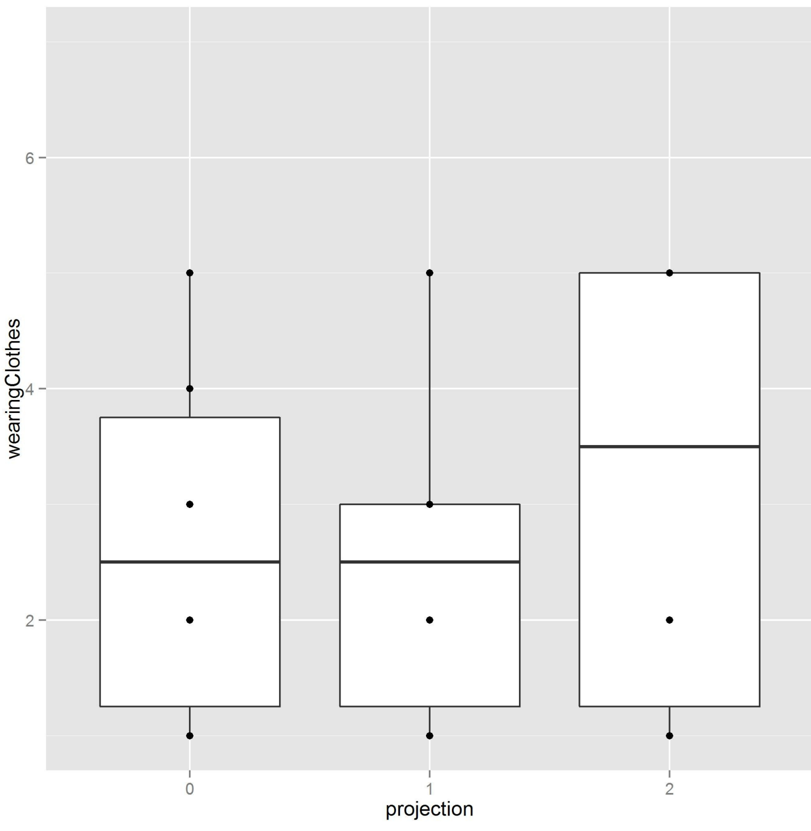
Feeling of body ownership



Feeling of real body turning virtual

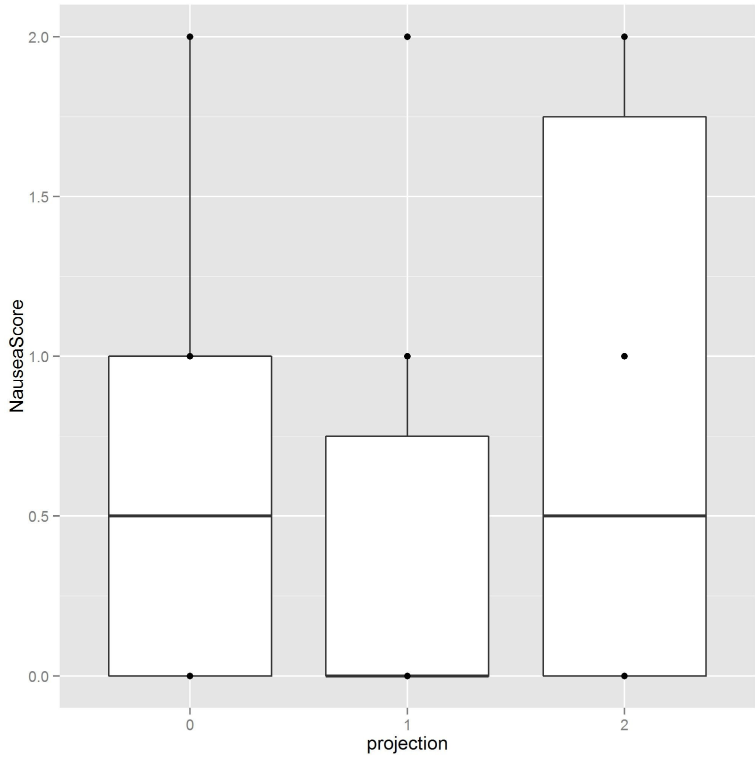


Feeling of wearing avatar's clothes



SSQ (less is better)

Nausea score



Oculus motor score