PERCEPTION IS NOTHING WITHOUT CONTROL (OF VELOCITY)

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The integration of haptic and visual perception in a virtual environment is a critical issue when there are delays between haptic and visual rendering. We suppose that integrated perception is affected of both the visual haptic discrepancies and the contact velocity of a target with an object. To test this hypothesis, we performed two experiments in which participants had to actively contact a virtual wall by using a haptic device. In the first experiment, the target velocity was held by the user (no-constant velocity task); in the second, the target velocity was kept constant at about 17mm/s (constant velocity task).We use the method of constant stimuli manipulating the delay of the haptic and visual rendering. Participants were asked to judge if they first perceived the visual or the haptic rendering when they contacted the virtual wall of 331N/m or 83N/m stiffness. The results show that performance in the no-constant velocity task is strongly affected by the stiffness, whereas in the constant velocity task, participants seemed to perceive delays correctly.

One of the main advantages of telepresence systems is they enable individuals to work in remote locations. Network technologies offer the manipulation of real or virtual objects using a haptic interface. A suitable manipulation requires accurate sensor information be provided to the operator, preferably through multiple senses (i.e. visual, haptic, and audio). The human perceptual system automatically integrates information available in all sense modalities (Varadharajan, Klatzky, Unger, Swendsen, & Hollis, 2008). However, network communication-induced artifacts occur in long-distance teleoperation, such as time delays and packet loss (Hirche& Buss, 2007).

This communication latency can sensibly affect the subjective experience of "presence" and task performance (Kaber, Riley, Zhou, & Draper, 2000; MacKenzie& Ware, 1993). This issue has received significant research interests in many fields, including human computer interaction and virtual reality, and results are not always unambiguous.

Several studies on the influence of delayed feedback have examined haptic and visual perception delay (Alhalabi, Horiguchi, &Kunifuji, 2003; MacKenzie& Ware, 1993; Lane et al., 2002; Kaber et al., 2000). Delays can modify a user's perception of virtual objects (i.e. perception of stiffness). In particular, Wu, Basdogan, and Srinivasan (1999) showed that stiffness perception is influenced by visual information. A recent study by Jay, Glencross and Hubbold (2007) examined the impact of delayed haptic and visual feedback. They found both visual and haptic delay retarded task performance in terms of difficulty of contact with the target. In contrast to the findings of Wu et al. (1999), they asserted that haptic delay had a greater impact on performance than visual latency.

Recently, Gleeson and Provancher (2011) found that the contact velocity of a target with an object did not have a significant influence on the perception of stiffness. Nevertheless, according to Wu, Abbott, and Okamura (2005) the velocity of the target played an important role: they found a better precision with low-level velocity. Similarly, Vicentini and Botturi (2008) underlined the relationship between contact velocity and stiffness on threshold values. Thus, in general, detection thresholds for visual and haptic delays may vary substantially (Adelstein et al., 2003; Allison, Harris, Jenkin, Jasiobedzka, &Zacher, 2001; Jay et al., 2007), probably depending on both the visual haptic discrepancies and the contact velocity of a target with an object.

Within this framework, we designed two experiments in which we proposed for the user two virtual surfaces. The first surface was rendered through the visual channel. The second one was experienced by the user through a force feedback, simulating a pliable surface. This was spatially separated by the first surface by a variable temporal delay.

Methods

We tested participants' perception in two multimodal experiments with temporal discrepancies between the visual and the haptic virtual walls (the visual wall was not haptically rendered, and the haptic wall was not visually rendered). The movement of the tool was connected in the visual scene to a small red sphere which acted as a proxy for the position of the tool tip in the virtual world. The task was to contact a virtual wall and immediately retract. To ease the haptic perception and to make the participants' movements easily controllable across the whole trial, we opted for a displacement along the z-axis (near-far horizontally). Thus, each subject was instructed to keep the elbow on a horizontal surface. Movements along the other directions were neglected.

Furthermore, to ease the visual perception we opted for a 2D scenario in which the red sphere moves along the y-axis (bottom-up, vertically). Basically, the sphere was seen "from above" and we map the near-far arm movements into a bottom-up sphere movement. In contrast, a 3D visualization where the sphere movement was coherent with the arm movement (near-far) would add possible depth perception problems or issues with movement along the x-axis (for example, the user could have moved the red sphere laterally). After each trial participants were asked to indicate which wall they first encountered. The response was done via key press and the data were logged.

Participant.A total of seven subjects were examined for Experiment I, and a different sample of seven subjects took part in Experiment II (age ranged from twenty to thirty y.o. all male and well experienced with haptic devices). Allparticipants were recruited within the laboratory staff. They were not informed about the experiment goals and were simply instructed how to attend to the task. All participants had normal or corrected-to-normal vision and had a normal sense of touch. They used their dominant hands to perform the tasks. All of them gave consent for the use of personal data for the purposes of this scientific research.

Apparatus.To simulate realistic force feedback, we used a Freedom 7S force feedback haptic device (MPB Technologies, Montreal, Quebec), which provides a workspace of about 170 W x 220 H x 330 D mm, a position resolution of 2µm and a resolution in force rendering of 40mN, with a maximum update rate above 1kHz. The pen-hold grasping configuration involved the thumb, index, and middle fingers. For the visual rendering, we used a 22-inch widescreen monitor, placed in front of the subject at a distance of about 50cm. The visual scene for our experiment was generated using the OpenGL library and rendered on the monitor. The force feedback returned by the haptic device was generated by a custom C++ program based on the provided Freedom API. The running OS was Windows 7 for the first experiment and Ubuntu 9.04 for the second.

Experiment 1 *– No constant velocity.* This experiment was aimed to detect the perception of temporal discrepancies between a haptic and visual surface in a condition of no constant velocity. The participants' tool velocity was not kept constant and they could use the velocity they preferred. The temporal delays were ±1250, 650, and 250ms. The stiffness values for the haptic wall were 331N/m and 83N/m, respectively the human skin and fat stiffness values (Gerovich, Marayong, & Okamura, 2004). The experimental design was a 2x6 within-subjects design.

Experiment 2 *- Constant velocity.*This experiment was aimed to determine if perception of delays between a haptic and a visual surface is influenced by the use of a constant velocity. For this reason, the subjects were asked to move at the same velocity as a yellow sphere (17 mm/s, optimal velocity to discriminate different stiffness, as shown in Vicentini &Butturi, 2010). In this experimental session, the stiffness factor was equal to the previous one, while temporal delays were ±1470, 882, and 294ms.

Statistical Analysis*.* Statistical analyses were conducted separately for each subject, each experiment, and for aggregate data using the R framework (R Core Development Team, 2011). Log-linear analysis was used to determine whether there were statistical significant differences due to stiffness, delay, or experimental session. For this purpose, delays were grouped in six categories:

First Haptic (FH) high (-1470 and -1250ms), FH medium (-882 and -650 ms), FH low (-294 and -250ms), First Vision (FV) low (250 and 294ms), FV medium (650 and 892ms), FV high (1250 and 1470ms). In log-linear analysis we considered the subject factor such as a random factor.

In addition, we fitted to subjective responses psychometric logistic functions using theNonlinear Least Squares algorithm *nlm* and computed PSEs and DLs.

Results

Psychophysical curves, PSEs, and DLs values for Experiment 1 and 2 are reported respectively in Figure 1 and Table 1.For experiment 1 the average contact velocity was 29.79 mm/s. Log-linear analysis was computed on the best fitting model, selected considering the lowest Bayesian information criteria (BIC) on the seven models reported below.

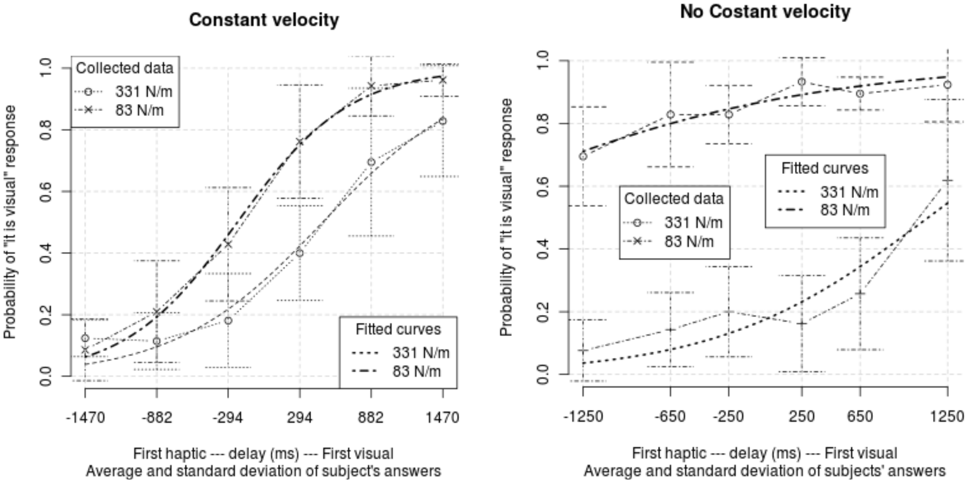

Figure 1: Psychophysical curves for constant and no constant velocity experiments

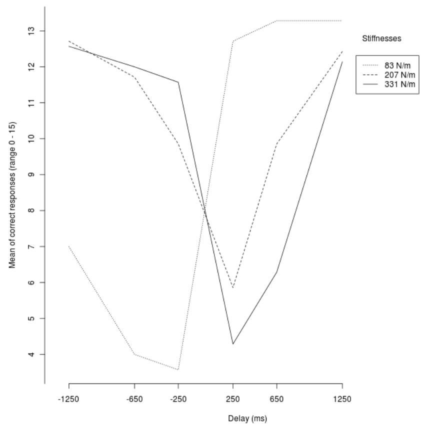

Figure 2: Interaction plot *stiffness:experiments*. In the y-axis the mean of subjective correct responses, in the x-axis the stiffness

In the saturated model (1) we used as fixed factors *delay*, *stiffness*, *experiment* and their 2-way and 3-way interactions, and as random factor *(1|subject)*. BIC criteria for each model are reported in Table 2. The resulting best fitting model is (5) and a graphical representation for *stiffness:experiments*interaction isreported in Figure 2.Tukey group-to-group comparisons for stiffness and experiment factors showed statistical significant differences (z = -4.401, p<.0001; z = 8.871, p<.0001 respectively). Tukey comparisons for delay factor are reported in Table 3.

$$y = \mathit{delay} + \mathit{stiffness} + \mathit{experiment} + \mathit{delay}:\mathit{stiffness} + \mathit{stiffness}:\mathit{experiment} + \mathit{delay}:\mathit{experiment} + \mathit{delay}:\mathit{stiffness}:\mathit{experiment} + (1|\mathit{subject}) \quad (1)$$

$$y = \mathit{delay} + \mathit{stiffness} + \mathit{experiment} + \mathit{delay}:\mathit{stiffness} + \mathit{stiffness}:\mathit{experiment} + \mathit{delay}:\mathit{experiment} + (1|\mathit{subject}) \quad (2)$$

$$y = \mathit{delay} + \mathit{stiffness} + \mathit{experiment} + \mathit{delay}:\mathit{stiffness} + \mathit{delay}:\mathit{experiment} + (1|\mathit{subject}) \quad (3)$$

$$y = \mathit{delay} + \mathit{stiffness} + \mathit{experiment} + \mathit{stiffness}:\mathit{experiment} + \mathit{delay}:\mathit{experiment} + (1|\mathit{subject}) \quad (4)$$

$$y = \mathit{delay} + \mathit{stiffness} + \mathit{experiment} + \mathit{delay}:\mathit{stiffness} + \mathit{stiffness}:\mathit{experiment} + (1|\mathit{subject}) \quad (5)$$

$$y = \mathit{delay} + \mathit{stiffness} + \mathit{experiment} + (1|\mathit{subject}) \quad (6)$$

$$y = 1 + (1|\mathit{subject}) \quad (7)$$

	Constant velocity		**No constantvelocity**	
	331N/m	**83 N/m**	**331 N/m**	**83 N/m**
PSE	-222.73	490.00	1123.74	-1250.00
DL	504.85	653.33	126.26	252.52

Table 1: PSEs and DLs for constant and no constantvelocity experiments

model	**df**	**BIC**
Saturated model (1)	25	1348.551
(2)	20	1315.637
(3)	19	1386.926
(4)	15	1518.566
(5)	15	1295.889
(6)	9	1587.594
Null (7)	2	1807.304

Table2: Bayesian Information Criteria

	Estimate	**Std. Error**	**z value**	**Pr(>|z|)**
{-294 -250} = {-1470 -1250}	1.07292	.24732	4.338	< .001
{294 250} = {-1470 -1250}	1.71444	.23179	7.396	< .001
{882 650} = {-1470 -1250}	2.05791	.22659	9.082	< .001
{1470 1250} = {-1470 -1250}	2.14143	.22549	9.497	< .001
{294 250} = {-882 -650}	1.27766	.19406	6.584	< .001
{882 650} = {-882 -650}	1.62113	.18782	8.631	< .001
{1470 1250} = {-882 -650}	1.70466	.18649	9.141	< .001
{294 250} = {-294 -250}	.64151	.15445	4.154	< .001
{882 650} = {-294 -250}	.98499	.14652	6.722	< .001
{1470 1250} = {-294 -250}	1.06851	.14482	7.378	< .001

Table 3 Tukey group-to-group comparisons for *delay* factor. Statistically significant results p > .001 omitted

Table 4 shows comparisons for the interaction stiffness: experiment. Finally, in Figure 3, the significance Tukey comparisons for delay: stiffness are graphically presented.

	Estimate	**Std. Error**	**z value**	**Pr(>|z|)**
83.Constant_velocity= 331.Constant_velocity	-0.36357	0.08297	-4.382	< 0.001
331. No Constant_velocity = 331.Constant_velocity	0.29611	0.08454	3.502	0.00243
83. No Constant_velocity = 331.Constant_velocity	-1.32832	0.12531	-10.600	< 0.001
331. No Constant_velocity = 83.Constant_velocity	0.65968	0.09168	7.195	< 0.001
83. No Constant_velocity = 83.Constant_velocity	-0.96475	0.13023	-7.408	< 0.001
83. No Constant_velocity = 331. No Constant_velocity	-1.62443	0.11293	-14.384	< 0.001

Table 4: Results for Tukey group-to-group comparisons for the *stiffness:experiment* factor

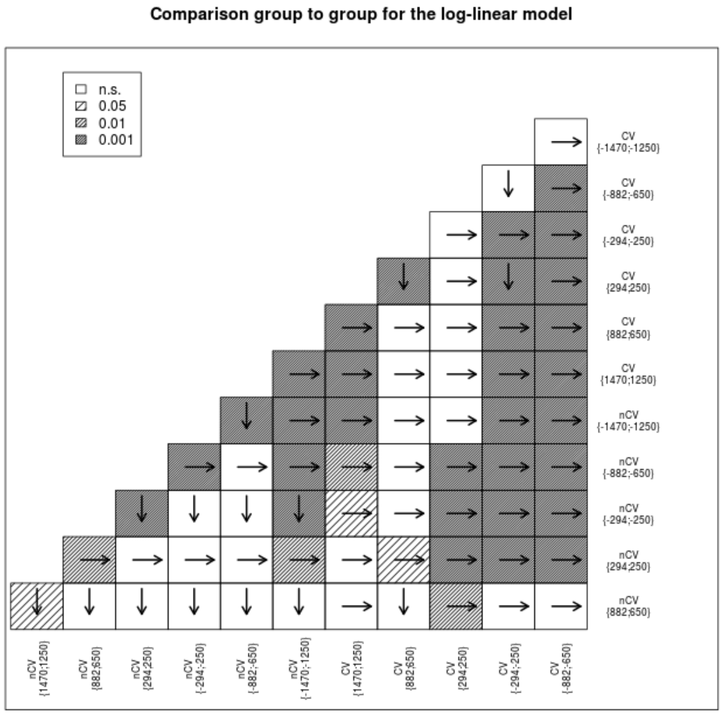

Figure 3: MISCA significance graphical representation for *delay:stiffness*(CS: Constant velocity, nCV: No Constant Velocity)

Conclusions

Based on inspection and statistical analysis, we found that with a constant velocity of 17 mm/sfor both 83N/m and 331N/m stiffness values, participants seemed to perceive delays correctly, although with more accuracy in the stiffest condition. When participants were able to use the velocity they preferred, the results showed that for the low stiffness value, the "it is visual" response is preferred for all delays used; whereas, for the high stiffness value, the trend is inverted, participants seemed to better perceive haptic rendering, except for the extreme visual delay value. In general constant velocity seemed to provide a better performance in perceiving delays; for the no-constant-velocity, which was around 29 mm/s, the responses seemed to be almost completely predicted by the stiffness. This result can be also seen by interaction plots (Fig. 2) which showed that the mean of correct responses in the experiment with constant velocity was high: independent of the stiffness used, the value was always around 0.8. When participants could choose the velocity to move the target only with a high stiffness value they answered correctly. With a low stiffness value such as high stiffness values, their judgments seemed to be very poor.

Globally ouroutcomes do not support Gleeson and Provancher's (2011) results. We found that the velocity of a target seemed to have a significant influence on the perception of stiffness. These data seem to be in agreement with Vicentini and Botturi's results, which indicated a relationship between velocity and stiffness perception.

Further efforts are needed to better understand whether constant velocity per se determines a better detection or whether these results are due to the fact that the velocity of 17mm/s eases the detection, given that it was always lower than the mean velocity used in the experiment with no constant velocity. Additional studies will be carried out in the future to give further insight into the role of contact velocity of a target on haptic and visual perception delay.

ACKNOWLEDGMENTS

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