THE ROLE OF VISUAL HAPTIC DELAY IN TELE-OPERATION PROTOCOLS

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Abstract

In tele-operation protocols developed for robot assisted surgery one of main challenges is the introduction of force-feedback, adding the possibility of manipulating delays between haptic and visual signals. In these conditions it is relevant to understand how the human performance is influenced by visual- haptic delays. In the present research, we study the role of temporal visual-haptic delays between a haptic and a visual rendering using a haptic device in a virtual environment. In a full factorial randomized design participants were asked to judge if they first perceived the haptic or the visual rendering. The delay levels (±1250, 650, 250ms) and the stiffness values of the pliable haptic wall (83, 207, 331N/m) have been randomly presented. Log-linear analysis shows that performance is strongly affected by delay (higher is the delay better is the judgment). Moreover, an interaction between delay and stiffness have been observed. Results will discuss in light of the weighted summation model.

Teleoperation system permits the individual to control in remote environments (Rosen & Hannaford, 2006). Audio, vision and haptic interaction is needed to enable the human operator to immerse into remote environment and it can aid a wide range of application scenarios, such as robotically mediated surgery (i.e. minimally invasive surgery, laparoscopy).

In recent years, many studies have focused on the added value of haptic feedback for task performance (Scandola, Vicentini, Gasperotti, Zerbato, & Fiorini, 2011; Okamura, 2009), i.e. the visual-haptic discrepancy in virtual reality environments (Scandola, Gasperotti, Vicentini, & Fiorini, 2012). In tele-operation protocols developed for robot assisted surgery haptic signals are sent bidirectionally between the master and the slave, and a global control loop is closed over the communication system. However, the transmission resources for communication networks could be limited and important communication constraints are compelled by communication technology and infrastructure in telepresence applications (Akyildiz, Pompili, & Melodia, 2004). High network traffic may also lead to network congestion and hence large transmission time delays (even over $1,000ms$) between haptic and visual signals and/or packet loss. This can lead to instability of the control system or degrade performance of a force-reflecting teleoperator. In addition this could be also a critical issue for patient safety in tele-operated robot-assisted surgery interventions. Therefore, transmission protocols are of high interest for the haptic modality since the loss of information should be perceptually unperceivable.

From this point of view, to deal the deadband-based haptic data reduction and psychophysics seems to be a needed way. It is shown, that the deadband-based data reduction can lead to high reduction rates. Psychophysical studies indicate that the loss of information induced by the algorithm can be considered unperceivable. Teleoperation protocols with time delay and perceptual-coding in time- delayed are considered (Hirche & Buss, 2007; Vittorias, Kammerl, Hirche, & Steinbach, 2009; Vittorias, Rached, & Hirche, 2010).

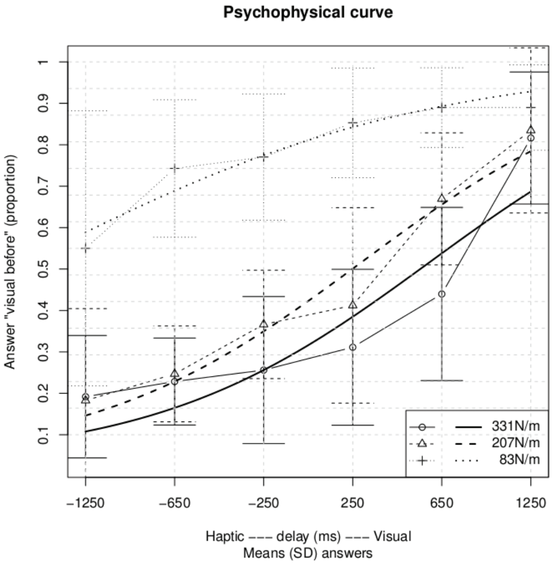


Figure 1: Graphical representation of subjective responses and psychophysical curves fitted on mean values

The weighted summation model (WSM), could be an useful model to predict how users perceive time delays in teleoperation protocols. This model, originally stated by Kuschel, Di Luca, Buss, and Klatzky (2010) but generalizable to different delay conditions (Ley, Haggard, & Yarrow, 2009), postulates that the perceived stimulus is a weighted sum of the effective stimuli as seen in other discrepancy studies (Scandola et al., 2012).

In this work we explore how the human performance is influenced by visual-haptic delays by studying the role of temporal visual-haptic delays between a haptic and a visual rendering. According to WSM, in our experiment Points of Subjective Synchrony (PSS, better described in Section *Statistical Analyses*) have to be influenced by the stiffness of the haptic component, according to the relation that at increasing values of stiffness of the haptic component, correspond a PSS collocation in the continuum of haptic-visual temporal discrepancies, in the direction that starts from the larger haptic delays following a decreasing trend, until the minor visual delays following an increasing trend, and vice versa.

Methods

In order to evaluate the responses to delays between haptic and visual renderings of a stimulus in teleoperation, we designed a Two-Alternative Forced Choice psychophysical experiment based on the method of Constant Stimuli. The experiment was divided in two phases: in the first phase, *"the exploration phase"*, participants had to move along a line in the horizontal plane, away from own body, a haptic tool until they contact a virtual wall (VW). The VW was both haptically and visually rendered, and between the two renderings there was a temporal delay. After each contact with the VW, the participant entered in the second phase, the judgment phase, where s/he had to choose which part of the VW was not delayed, if the haptic or the visual one (that is, they had to answer whether they first perceive the haptic or the visual signal).

We tested six temporal delays (±1250, 650, 250ms) and three haptic stiffness (83, 207, 331N/m) for the haptic rendering. Stiffness levels were selected to simulate pliable objects actually present in the human body (Gerovich, Marayong, & Okamura, 2004): the human fat (83N/m), the human skin (331N/m) and an intermediate stiffness (207N/m).

Participants. Seven subjects took part to the experiment (all right-handed, 2 females, age ranged from 20 to 31 y.o.), with no previous knowledge of the experimental setup. Each experiment lasted about 40 minutes, and no money compensation was planned. All participants had normal or corrected-to-normal vision and without any history of somato-sensory disorders. All participants gave the consent for anonymous use of personal data for the purposes of this scientific research.

Apparatus. Realistic force feedback was rendered using a Freedom 7S force-feedback haptic device (MPB Technologies, Montreal, Quebec). Its workspace can be represented by a parallelepiped about $170mm$ wide, $220mm$ tall and $330mm$ deep. The Freedom is a high performance device, with a position resolution of $2\mu m$, a resolution in force rendering of 40mN and a maximum update rate above 1kHz. The base of this device was positioned so as to be comfortably reached with the subject's dominant hand. The pen-hold grasping configuration involved the thumb, index, and middle fingers. The hand operating the device is not anchored to the desk, hence neither the wrist nor the elbow were provided with a grounded support. For the visual rendering we used a 20-inch wide screen monitor, placed in front of the subject at a distance of about $50cm$.

The implementation of the virtual environment relies on the OpenGL library and on the library provided by the haptic device producer. The VW was graphically rendered in a tridimensional perspective, while the tool tip was connected to a virtual red sphere.

Procedure. We instructed participants saying: "In this virtual environment you have to move the tool close-far along an imaginary line until touching the target VW. The target is graphically and haptically rendered, but between these two components there is a temporal delay. The delayed component randomly varies in each trial. You could enter in contact with just the visual, the haptic component or both components, indifferently. After each trial there will be a black display asking you if you perceived first the haptic or the visual component. Please answer via key press, '1' for the visual component or '2' for the haptic one".

In the *exploration phase* participants had to move a red sphere in direction of the VW, until the contact. The movement of the red sphere was connected with the movement of the haptic tool, and it worked such as a proxy for the position of the tool tip in the virtual world. The VW was rendered in a tridimensional perspective in order not to give cue about the graphical contact point before the contact.

In the *judgment phase* participants had to indicate which was the rendering they firstly encountered in the previous phase. The response was given via key press ('1' for the visual rendering, '2' for the haptic one), and the data were recorded.

Delay and stiffness factors were randomized for each participant, obtaining a 6×3 within-subjects design, and every combination was repeated 15 times, for a total of 270 trails. For our analyses, we logged participants' responses.

Statistical Analyses. Statistical Analysis. Statistical analyses were conducted for each subject and for aggregate data using the R framework (R Development Core Team, 2011). Psychometric functions were fitted using the Nonlinear Least Squares algorithm *nlm* over calculated probability of "Visual" response for all stiffness conditions. These functions were defined by the Gauss-Newton logistic function (1):

$$y = \frac{1}{1 + e^{-\beta(x-\psi)}} \tag{1}$$

where the experimental data are y (the subjective response) and x (the delay between

	$331N/m$	$207N/m$	$83N/m$
Mean	762.99	304.83	−1004.69
SD	415.89	520.56	371.34

Table 1: PSS means and SD values

	dof	AIC	BIC
eq. (2)	19	159.1790	213.0684
eq. (3)	9	272.9697	298.4962
eq. (4)	2	295.8183	301.4909

Table 2: AIC and BIC values

visual and haptic stimuli), whereas the parameters to be identified ψ and β are related to the location and the slope of the curve respectively. For each psychometric function the Point of Subjective Synchrony (PSS) was calculated. PSS is the stimulus that elicits 50% of "visual" responses, it is related to the ψ of the psychometric function and it was calculated at proportion 0.5.

Moreover to identify differences in participants' performance we have used the log-linear analysis test, applied to participants' responses, using as fixed factors the delays and the stiffness, and subjects as random factor. We selected the best fitting model among the saturated model, the null model, and the model that considers only the main factors using both Akaiake Information Criterion (AIC) and Bayesian Information Criterion (BIC).

Results and Discussion

Psychophysical curves were fitted to compute PSSs (Table 1). For this analysis we used subjects' responses "it is visual". In Figure 1 are graphically reported the proportions of participants' responses and the fitted psychometric functions on these data.

For the log-linear analysis we selected the best fitting model among the saturated one (2), the null model (4), and a model that considers only the main factors (3).

In Table 2 are reported the AIC and BIC indexes. Following both criteria we selected the best-fitting model, the saturated model (2), to understand which are the factors that could lead to a correct answer.

$$y = \text{delay} + \text{stiffness} + \text{delay} : \text{stiffness} + (1|\text{subject}) \tag{2}$$

$$y = \text{delay} + \text{stiffness} + (1|\text{subject}) \tag{3}$$

$$y = 1 + (1|\text{subject}) \tag{4}$$

where y are the correct subjective responses, *delay* and *stiffness* the main fixed factors, *delay:stiffness* the interaction and $1|subject$ is the random factor.

It is important to highlight that this analysis was done considering the correct responses. It means that for delays where haptic was first, we considered the answers "it is haptic", and where visual was first we considered answers "it is visual", while, previously, to fit psychophysical curves we used answers "it is visual" in all cases.

In Table 4 and 3 results of the significant contrast analysis for the log-linear model Stiffness and Delay main factors have been reported respectively. They show that for the delay factor almost all comparisons reach the statistical significance involve extreme delays. This is probably due to an extreme delayed component which favors the perception of the no-delayed component, while the stiffness factor statistical significant differences are between $83N/m$ and $207N/m$ condition.

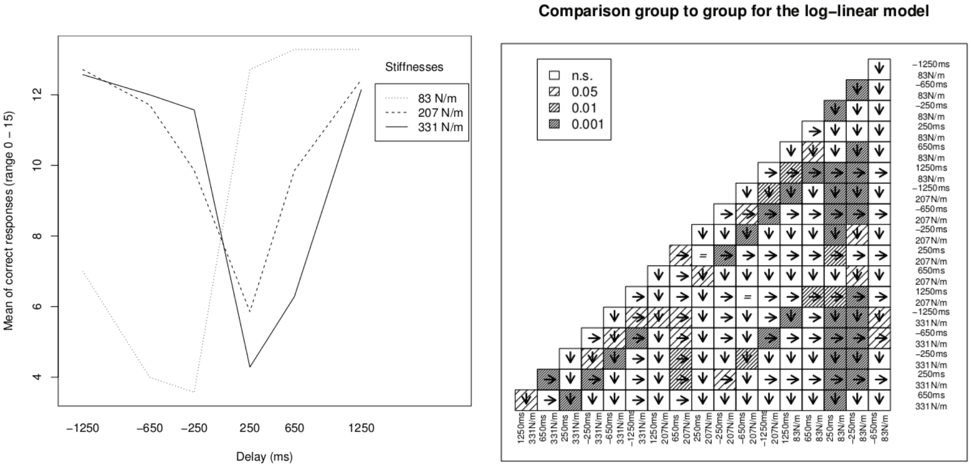
In Figures 2(a) and 2(b) there are two graphical representations for the interaction *delay:stiffness* and statistical significances among cells. Figure 2(a) presents the interaction

	Estimate	SE	z value	p
$-250 = -1250$	$-.337$	.111	-3.048	.0283
$250 = -1250$	$-.418$	.112	-3.748	.00247
$1250 = -650$	.424	.102	4.150	$< .001$
$1250 = -250$	.531	.106	5.017	$< .001$
$1250 = 250$	.613	.107	5.725	$< .001$
$1250 = 650$	.297	.0955	3.108	.0231

Table 3: Results for Tukey group-to-group comparisons for the *delay* factor (no statistical significant results omited)

	Estimate	SE	z value	p
$207 = 83$	.233	.0789	2.947	**.00884**
$331 = 83$	.141	.0818	1.719	.198
$331 = 207$	$-.0920$	.0746	-1.233	.433

Table 4: Results for Tukey group-to-group comparisons for the *stiffness* factor (statistical significant results in bold)



(a) Interaction plot

(b) MISCA representation

Figure 2: (a) Interaction plot for *delay:stiffness* (b) MISCA statistical significance graphical representation for *delay:stiffness*

plot, in Figure 2(b) shows the MISCA plot, where cell represent statistical significance and arrows indicate which group has the larger mean.

From Figure 2(a) it is possible to note the constant tendency in the $83N/m$ condition to underestimate the possibility that the visual component could be delayed, while the influence that $207N/m$ and $331N/m$ have on performance is more complex. Generally, when the haptic component is delayed participants had a correct response (in a similar way to the $83N/m$ condition). This observation could lead us to deduce that the performance is influenced only by the stiffness. However, from both Figure 2(a) and 2(b) it is possible to note that a stiffer haptic component facilitates more correct answers also when the haptic component is strongly delayed.

In conclusion, PSSs are distributed according the WSM, and log-linear analysis seems to show that the model is useful to understand the collocation of PSSs, however it does not predict participants' performance in all cases. Globally our data show that stiffer haptic components permit an easier perception not only of visual-haptic discrepancies, but also the direction of these discrepancies. Further efforts are needed to better understand which factors lead the human perception of visual-haptic discrepancies in a virtual environment and the validity of WSM. In our experiment the visual component of VW is kept constant, avoiding preliminary visual cues about where there will be the graphical contact between the tool and the VW. Further studies will consider different graphical characteristics and how these characteristics influence the human perception.

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