COMBINED SCALE FACTORS FOR LATERAL AND YAW MOTION RENDERING

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Abstract

Fidelity of driving simulation does not depend only on the capacity of the simulator to render motion close to reality, but rather on its capacity to elicit perceived motion close to reality. Evaluating fidelity requires therefore basic knowledge of motion perception features, in particular regarding the evaluation of just noticeable differences (JND). This study aimed at evaluating the JND for inertial motion perception in slalom driving at constant velocity, during which the only inertial cues are lateral and yaw acceleration. Although both cues are physically coupled in a car, it is not known whether their JNDs are also coupled, and whether strictly respecting this coupling is necessary during simulation. The experiment was conducted using Renault's ULTIMATE driving simulator in which scale factors (gains) could be applied independently on both cues. Subjects reported whether they detected a difference between a reference drive of the slalom where gains of 0.5 were applied on both lateral and yaw acceleration rendering, and a test drive with a randomly chosen couple of gains. Subjects judged this difference according to several psychological criteria relevant for the evaluation of a driving situation (perceived manoeuvrability/difficulty/dangerousness). Changes in the drivers' behaviour, evaluated through the comparison of angular velocity profiles of the steering wheel, is also analysed as an indicator of a difference in perceived motion. Each subject rated only one gain configuration, and data of all subjects were analysed together. This experimental methodology lead to the definition of average bidimensional JNDs around reference gains. Perceived dangerousness of the situation appears to be more relevant than the two other subjective criteria for driving evaluation. Results confirm the existence of a large tolerance on the amplitude of rendered lateral acceleration. The experiment is still ongoing and future results should enable to precise whether coupling has an impact on simulation fidelity.

Résumé

La fidélité d'une simulation de conduite ne dépend pas directement de la capacité du simulateur à rendre le mouvement de manière exacte, mais plutôt de reproduire la perception d'un mouvement proche de la réalité. L'évaluation de cette fidélité nécessite la connaissance de la perception du mouvement, en particulier l'évaluation des *just noticeable differences* (JND). Cette étude a pour but l'évaluation des JND pour la perception des mouvements inertiels lors d'une conduite en slalom à vitesse constante, pendant laquelle les seules informations inertielles sont les accélérations latérale et de lacet. Bien que ces deux grandeurs soient liées physiquement pour un véhicule, on ne sait pas si leurs JND respectives sont couplées aussi, ni s'il est indispensable de respecter ce couplage lors d'une simulation. L'expérience a été menée sur le simulateur ULTIMATE de Renault, et les facteurs d'échelle, ont été modifiés indépendamment. Les sujets devaient signaler s'ils détectaient une différence dans la conduite entre une situation de référence avec des gains de 0.5 sur les accélérations latérale et de lacet, et une conduite test avec un couple de gains choisi aléatoirement. Les sujets devaient juger cette différence en fonction de plusieurs critères psychologiques liés à l'évaluation d'une situation de conduite. Les changements dans le comportement du conducteur ont été également analysés en tant qu'indicateur de la perception d'une différence de condition de conduite, par l'étude des profils de vitesse angulaire du volant. Les résultats de tous les sujets ont été analysés dans leur ensemble, chaque sujet étant associé à un seul couple de gains. Cette méthodologie expérimentale a conduit à la définition de plages 2D de JND autour du couple de gains de référence, pour une population donnée de sujets.

Le niveau de danger perçu semble le critère subjectif le plus adapté à l'évaluation des conduites. Les résultats confirment l'existence d'une tolérance importante sur l'amplitude de la restitution de l'accélération latérale. L'expérience continue, et les futurs résultats devraient permettre de précise si le couplage a un impact sur la fidélité de la simulation.

Introduction

The evaluation of the fidelity of a simulator depends on the driver, his perception of movement, and on his actions during the simulation. Two approaches are used to measure it: subjective evaluations, and the characterization of behavioural realism. Subjective evaluation is mainly used for psychophysical experiments when sensation of movement has to be described, but can also be adapted to driving situation (Fortmüller et al. 2008) or to flight simulation (Groen et al. 2000), when subjects are asked to evaluate the conditions of a task, after technical parameters modifications. Behaviour during the task can be observed through driving performance of spatial and temporal manoeuvres characteristics such as speed in curves (Reymond 2001), trajectory deviations, or actions on the steering wheel (Boer et al. 2001, Colombet et al. 2008).

Motion perception has been shown to be tolerant to large discrepancies between self-motion and simulated visual information (Jaekl et al. 2005). Fortmüller et al. (2005, 2008), found an area of variable yaw values where no noticeable difference was perceived in driving, and they demonstrated in a second experiment that this area could be extended with the introduction of tilt acceleration. In the same direction, our objective is to be able to build a map of useable settings for each context of simulation.

In dynamic simulators, 1:1 scale rendering of inertial cues (when the platform produces exactly simulated movements) has been demonstrated not to be necessarily the best solution (Groen et al. 2000, Dagdelen et al. 2006). In our study, we focus on the fidelity of simulation according to motion scale factors applied on lateral movement and yaw. Preferred gains cannot be defined by precise values but rather by ranges of tolerated values. Establishing a cartography of these ranges would enable simulator designers to choose optimal settings according to technical constraints. To this end, differential perception thresholds are studied here. Previous works on sensitivity to movement studied absolute detection thresholds on acceleration in complete obscurity, (Grabherr et al 2008) or with passive subjects (Van der Steen 1998), yet these thresholds are known to be modified in presence of visual information (Huang and Young 1981), as well as by interactions with the environment. These findings are therefore not sufficient to recommend gain values settings for a driving situation.

Another related fundamental question is whether the perception of different degrees of freedom is cross-coupled. Here, we focused on gains on lateral movement and heading angle: when a car follows a curvilinear trajectory, in normal conditions, its orientation is approximately tangential to this trajectory, and heading and lateral acceleration are physically coupled. By modulating both at the same time, we assess whether a coupling effect is present in movement perception as well, which means that when acting on two parameters, their respective effect on motion perception is different than when each parameter is observed independently. Movement perception is not only the addition of information provided by different sensorial cues, but is part of a global process computing this information. In the case of driving in a curve, self-motion could be interpreted through an internal model, integrating the relationship between different dynamic parameters, similar to otolith-semicircular canals interactions which have already been put into evidence for the disambiguation of otolithic information (Angelaki et al. 2004, Laurens et al. 2007).

We chose to measure the effect of downscaling the rendering of lateral acceleration and yaw on drivers' perception and performance. The aim is to be able to associate to a given driving context (driver, manoeuvre, vehicle characteristics) a cartography of scale factors usable for the coupling of these cues, by (1) evaluating the tolerance ranges around a reference tuning, and (2) identifying the interdependency between the tunings of yaw and lateral motion cues rendering. In the present experimental setup, both scale factors were controlled independently, thus allowing the introduction of a conflict between yaw and lateral motion cues.

Methods

The experiment was carried out at Renault Technocentre on the driving simulator ULTIMATE, which could reproduce without distortion the acceleration profile involved in the slalom scenario. Technical details about performance of ULTIMATE are available in (Dagdelen *et al.* 2006).

Slalom specifications

The visual environment used in this experiment consisted in a simple straight road with 15 pylons between which subjects had to drive a slalom. The pylons were regularly spaced with a 62.5m separation distance. The 8th pylon was a bit displaced (82.5m from the 7th pylon, and 42.5 from the 9th pylon) in order to introduce a disturbance and to avoid habituation during the slalom. This slalom was driven at a constant 70km/h velocity.

The only inertial cues involved here are the lateral acceleration, yaw acceleration and roll acceleration. The latter being more related to the each car particular dynamics, this factor is not specifically studied here.

By approximating the trajectory of the vehicle on the regular parts with a sinusoidal curve, the lateral acceleration amplitude and frequency can be estimated to be respectively around 0.12g and 0.16Hz, which within the rendering capabilities of the lateral rail of the simulator (max. acceleration: 5m/s²; bandwidth : 0-5Hz@-3dB).

There is a physical coupling between lateral inertial cues and yaw rotation cues in a car that follows a curvilinear trajectory without slipping with small steer angles :

$$h = \frac{\dot{y}}{v} \qquad \dot{h} = \frac{\ddot{y}}{v} \qquad \ddot{h} = \frac{\dddot{y}}{v}$$

where *h* is the angle between the vehicle and the axis of the road (yaw angle), *y* is the lateral position of the vehicle on the road and v is the velocity of the car.

The present study also aims at answering the question whether this relation should be kept while modifying motion gains for yaw and lateral acceleration rendering.

Experimental procedure

Slalom driving

After starting the vehicle, subjects were asked to accelerate, stabilize the vehicle velocity at 70km/h, in 4th gear (manual gearbox), and place the vehicle on the left lane after reaching this target speed. The slalom began after a few seconds. Subjects were asked to drive smoothly and to pass as close as possible to the pylons.

Procedure
Each subject drove the slalom, twice in a reference condition in order to be familiar with the task and with simulator driving. In this reference condition, a scale factor (gain) of 0.5 was applied on both lateral and yaw acceleration rendering.
At the 3rd driving session, scale factors were changed and the subject was asked to indicate whether a change was perceived, according to several criteria related to the driving situation. The following questionnaire was administrated:

"Did you notice any difference between test drive and reference drives concerning:

- *manoeuvrability of the car*
  - *less manoeuvrable (-1)/ same (0) / more manoeuvrable (1)*
- *difficulty to perform the task*
  - *easier (-1) / same (0) / more difficult (1)*
- *immersion in the situation / perceived dangerousness of the situation*
  - *less dangerous (-1) / same (0) / more dangerous (1)"*

Answers were collected for randomly chosen couples of scale factors on lateral and yaw acceleration, drawn from a continuous uniform distribution in the product of intervals [0 1]x[0 0.7]. This method allows an exploration of the stimulus space independent of a fixed *a priori* granularity of a grid.

A sequence of three slaloms took approximately 15 min. Each subject participated in one to five of these sessions. This paper reports the results for 41 measures collected with 17 participants.

Subjective data analysis

The objective of this analysis is to extract from subjective answers an area of constant perception for each evaluated psychological factor. This area can be defined as the set of couples of scale factors that are predicted to be neither rated 1 nor -1 in more than 50% of the comparisons with the reference condition. The proposed method is to estimate for each couple of scale factors the mean of subjective answers, which is a value in the interval [-1 1]. A value greater than 0.5 or lower than -0.5 implies indeed that the considered condition will be rated 1 or -1 in more than 50% of the trials. Although this bidimensional JND may be subject to inter-subject variability, this methodology is believed to converge to an average of the JND over the tested population. This method presents the advantage of providing this estimate with a shorter duration of the experimental sessions for each subject, as compared to the application of a method of constant stimuli for all subjects before averaging.

The continuous sampling of stimulus space requires some interpolation of data between the measured points in order to estimate the searched area. This interpolation has to be non parametric since no mathematical definition of the surface can be given *a priori*. Indeed, classical shapes of psychometric curves cannot be used in this context since there is no evidence of a monotonic mathematical relation between controlled parameters of the stimuli and studied factors. The interpolation consisted in estimating the value $r(g)$ (average answer) for a given couple of scale factors g as the weighted average of measured answers $(r_i)_{1\leq i\leq N}$ for gains $(g_i)_{1\leq i\leq N}$, with weights $w_i(g)$ decreasing with the Euclidean distance $\| g-g_i \|$:

$$r(g) = \frac{1}{\sum_{i=1}^{N} w_i(g)} \sum_{g_i \in G} w_i(g) r_i \qquad \text{,with } w_i(g) = e^{-\frac{1}{2}\left(\frac{\|g-g_i\|}{\sigma}\right)^2}$$

The parameter σ defines the extent of the influence of measured points on the surface. This value controls the smoothness of the final surface. Using very small values of σ will result in surfaces that will perfectly fit all the answers but will be very sensitive to noise in the measurement, leading to a so-called overfitting problem. On the contrary, high values of σ will smooth the surface and may reduce possibly interesting features. In the following, a value of $\sigma = 0.15$ is used, which is the order of magnitude of the mean distance separating any value g_i from its closest neighbour.

The variability of this estimate is computed using a statistical bootstrapping method. The final estimate of the surface is in the median of the bootstrap result, and the variability of the result at each point is computed as the difference between the 1st and 3rd quartiles. The estimation of this variability of one point of the surface can be used in an adaptative procedure as a criterion to choose the sequence of measurements: adding a measure where this variability is maximum will improve estimate of the surface.

The estimation of the boundary of the constant perception area can therefore be computed by drawing the iso-contours of the surface at the levels -0.5 and 0.5.

Objective data analysis

Steering wheel angle was recorded during the experiment at 20Hz. The RMS of the high frequency part (above 0.2Hz) of the angular velocity of the steering wheel is analysed as an indicator of the smoothness of driving. The ratio of this value during test drive and the second reference drive was computed to compare all trials. The angular velocity of the steering wheel angle was computed by a finite difference and treated with a 5Hz low-pass filter to remove noise due to this numerical derivation. The high-frequency part of the signal was extracted using a 0.2Hz high-pass filter to remove the nearly sinusoidal component at 0.16Hz of the signal due to slalom driving. The final signal is representative of the small corrections subjects applied on the steering wheel to control the trajectory of the vehicle.
From all of ratios obtained during the experiment, an approximation surface is computed using the same method as precedent.

Results

Subjective data

Figure 4 show the results of the evaluation of the manoeuvrability of the vehicle. The collected answers are plotted on Figure 4(a), grouped by the values of the answers (‘Less manoeuvrable’, ‘Same’, ‘More manoeuvrable’). The central graph shows ‘same’ answers are

quite well grouped and localized in a region around the reference condition (0.5; 0.5). This region is vertically stretched, *i.e.* more extended along yaw acceleration gains axis than along the lateral acceleration axis. The existence of a coupling between gains is not obvious in the data.
Graphs 1 and 3 of Figure 4(a) show that a confusion of answers out of this region. ‘More manoeuvrable’ and ‘less manoeuvrable’ answers cannot be located in separated proper regions. This could mean that the transition zone around the area of strictly equivalent perception covers a large region and subjects answered randomly in this zone. This could also be due to between subjects differences in the sensitivity to manoeuvrability changes. An alternative hypothesis is that the question was ambiguous for some subjects, and qualifying the type of change (‘more’ or ‘less’) was interpreted differently during the experiment, despite a correct detection.
The predicted surface of average answer generated from these data is plotted on Figure 4(b) – left. The right part of the figure shows the variability of this predicted surface at each point as computed by the bootstrapping method. The 4th graph of Figure 4(a) shows the iso-contours of this surface at levels 0.5 and -0.5. The numerical algorithm used to compute this surface favors the first hypothesis and therefore the predicted extension of the area of equivalent perception is wide.

Figure 5 shows the results of the evaluation of the difficulty of the task. According to Figure 5(a) the region where ‘same’ answers are given is still not clear and, as precedent, the qualification of detected differences is confused. This also leads to a prediction of a large area of equivalent perception as shown in Figure 5.

Figure 6 shows the results of the evaluation of the perceived dangerousness of the situation. According to Figure 6(a) the regions of each type of answers are clearly separated, meaning that the question was unambiguous and that all subjects had an approximately equivalent sensitivity to this factor. Figure 6(b) illustrates the predicted area of equivalent perception, which does not seem to depend much on yaw gains.

Objective data

Figure 3 (left) shows the estimated ratios for each gains, which are interpreted as indicators of variations in the smoothness of driving between reference and test conditions. The variability of this surface estimate is large near the borders of the explored set of gains, limiting possible conclusions on the impact of scale factors there. More measurements are necessary in these areas to improve the reliability of the surface estimate.
In the central region, which is less subject to variability, increasing gain on lateral acceleration seems to increase the estimated ratio, *i.e.* decreasing smoothness of driving. The impact of yaw gain is not visible.

Discussion

The results presented here focus on the effect of gains applied to the couple lateral acceleration/yaw, around which we tried to characterize a domain of tolerance for driver perception. Evaluation of dangerousness of the situation only provides clear results: the influence of lateral acceleration gain is observable on this factor. However, the coupling between yaw and lateral acceleration rendering is more difficult to assess from the collected

data. The coupling might be a second order phenomenon that requires more measurements to be clearly observed. Grabherr et al 2008 estimated the yaw detection amplitude at the frequency of the slalom to be around 2°/s. The difficulty to measure the coupling could also be due to yaw velocity amplitudes involved in this experiment close to this threshold. However, this value has been measured in different conditions, in darkness, with passive subjects, and could therefore be different in this study.
Results on the perceived maneuverability of the car and the difficulty of the slalom were more ambiguous and no clear tendency appears. This is probably due to different interpretations of these criteria by subjects interrogated. For example, maneuverability of the vehicle have been felt differently from one subject to another, some considering that a car which is very mobile and reactive has a better handling, whereas other ones prefer actions on the steering wheel producing smoother reactions of the vehicle. On the other hand, criteria proposed here are tightly linked, and are selected to describe realism of the simulation when taken from every angle. This proximity can also lead to a confusion. A better definition of the notions to analyze would be necessary to prevent these biases.

We made the experiment on a group of different subjects, each one for one measure, so that the final results correspond to a global group of drivers. There is a great variability between subjects, and repeatability within subjects is not always verified for driving in simulators (Dagdelen et al. 2006). There is no need to use expert drivers with repeated conditions for our kind of studies, and taking a large panel of subjects provides more reliable observations, valid for a whole group of subjects. Moreover, if the methodology proposed here is applied to the whole values acceptable by the simulator, and provide preference areas for the couple lateral acceleration/yaw, we may be able to demonstrate that for a particular task, some settings are satisfying for a proportion of persons within a group. It would then be possible to deduce the number of subjects to test on the wanted task, and estimate the reliability of the results obtained. And another benefit is a time of test reduced for each subject.

One limit of the present study is the exploration of scale values inferior to 1:1. It could be instructive to enlarge this method to gain values above 1, in order to have a more global vision of preference maps in the field of utilization of dynamic simulators. Anyway, other measurements will be performed, in order to improve results significance, and to fill areas of exploration where data are insufficient or missing.

The practical applications of this study typically require definition of domains of preference usable for simulator settings, especially for driving situation that explore limit conditions of vehicle dynamics, such as systems of trajectory correction (ESC), or for virtual prototype definition related driving comfort evaluations.

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Figures

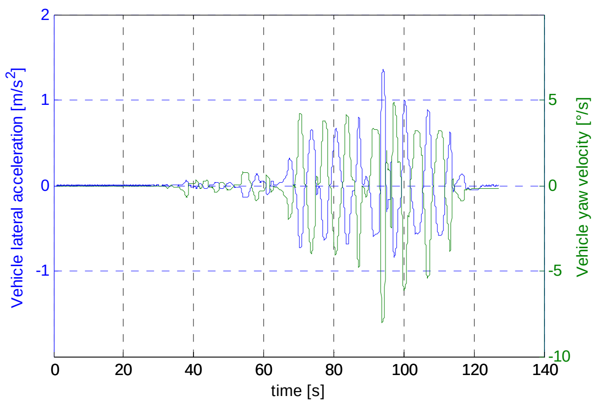


Figure 1 – Vehicle lateral acceleration and yaw velocity during a slalom maneuver. During the experiment, motion commands of the dynamic platform are generated by scaling plotted values according to gain configuration of the condition.

Figure 2 – Visual environment

Figure 3 – Variations of smoothness of driving

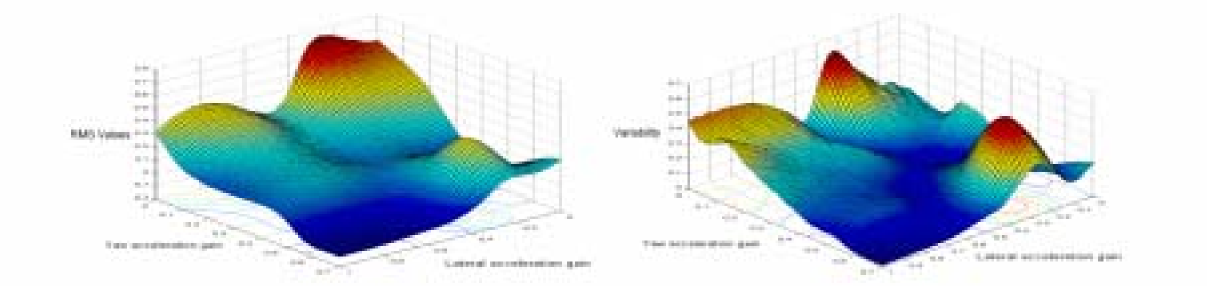
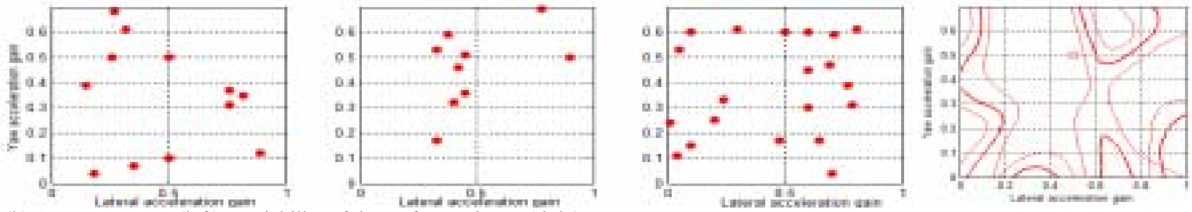


Figure 4 – Evaluation of maneuvrability.

(a) Verbal reports - (1) 'Less manoeuvrable', (2) 'same', (3) 'More manoeuvrable', (4) Estimated boundary of the equivalent perception area (thick line). Uncertainty on this estimate (dotted lines)



(b) Average answer (left) , variability of the surface estimate (right)

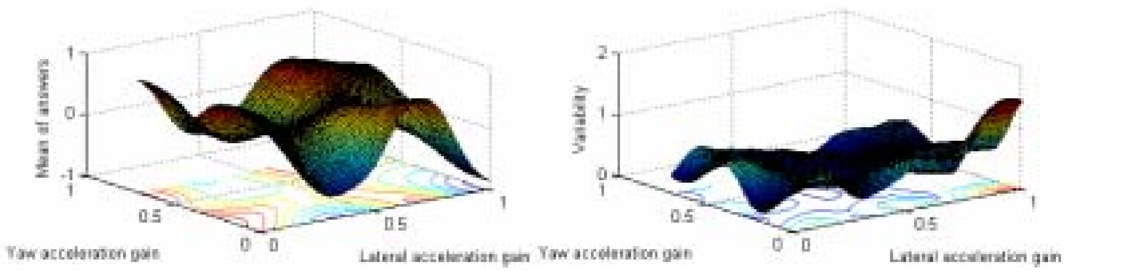
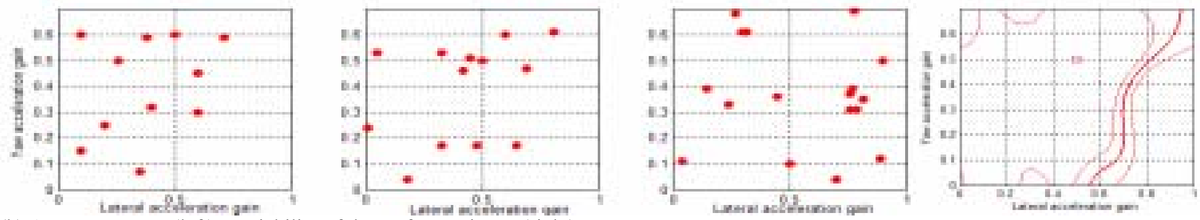


Figure 5 – Evaluation of the difficulty of the task.

(a) Verbal reports - (1) 'Easier', (2) 'same', (3) 'More difficult', (4) Estimated boundary of the equivalent perception area (thick line). Uncertainty on this estimate (dotted lines)



(b) Average answer (left) , variability of the surface estimate (right)

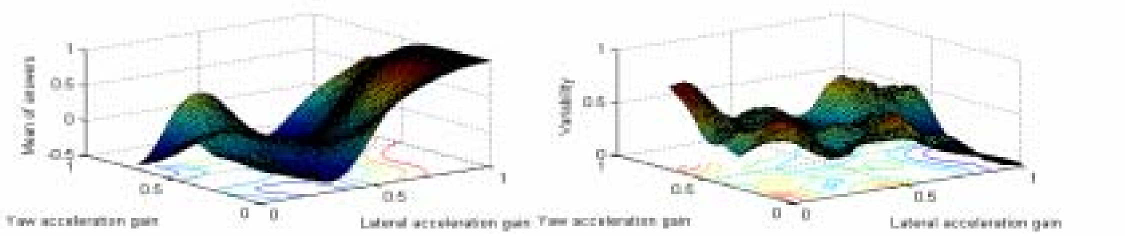
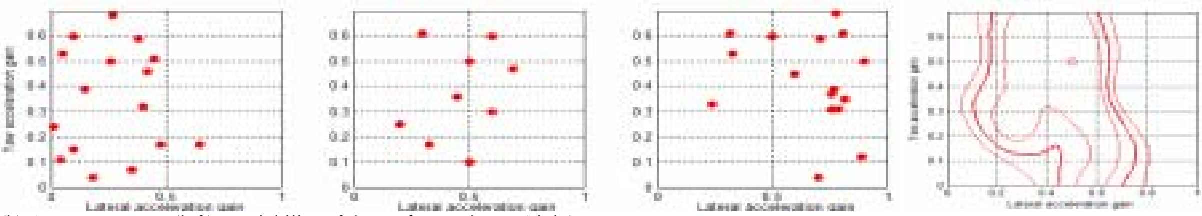


Figure 6 – Evaluation of the dangerousness of the situation.

(a) Verbal reports - (1) 'Less dangerous', (2) 'same', (3) 'More dangerous', (4) Estimated boundary of the equivalent perception area (thick line). Uncertainty on this estimate (dotted lines)



(b) Average answer (left) , variability of the surface estimate (right)