Application of a Relative Visual Performance Model in a Virtual Reality Immersive System

Benoit Perroud, Stéphane Régnier, Andras Kemeny, Frédéric Mérienne

Abstract—Visual simulation is increasingly taking part in the creation design of new products, especially in the automotive industry. In order to be a fully trustful tool, simulation must be realistic and thus look for specifications very close to the human vision perks. As part of an evaluation process of user experience realism in a Virtual Reality system, we focus in this paper on one of the core characteristics of vision: the relationship between contrast and luminance. The experiment relates to Rea and Ouellette model and aims to validate its reaction time predictions. The performance is defined as the inverse of the reaction time. The performance hence increases when the reaction time decreases. Our results disclose a major difference in behavior compared to the theoretical predictions. Causes could come from the lighting conditions. In our opinion Rea's RVP model should not be used in the field of Virtual Reality to grade a system's performance with respect to the human vision.

Index Terms—Contrast, Luminance, Visual Performance, Virtual Reality

1 Introduction

Simulation, through the use of simulators and immersive display systems, becomes a more and more preponderant factor in the development of new products. In the automotive industry, it is largely used for relative and, sometimes, absolute validation of vehicle systems designs, such as Human Machine Interface (HMI) and Advanced Driver Assistance Systems (ADAS), as well as human factors studies [1]. Manufacturers hence need trustful tools in order to make decisions.

The display part of a simulator must be treated with great care and the measure of its quality appears to be essential (as an example, for driving simulators, 90% of the information used by a driver are claimed to be visual, though it is yet to be fully proved numerically [2]). Our goal is to make the simulator achieve one of the five acceptations of realism [3]: the information provided to the sensory system of the body (in our case, the eyes) are the same that one could have in a real life experiment.

This paper focuses on one of the core characteristics of vision: the relationship between contrast and luminance. These two attributes are closely linked and are key factors in the trustfulness of a display. The aim is to be able to describe how much contrast and luminance one needs in Virtual Reality in order for the visual system to work as it would in real life, what is their relationship and how the human visual system behaves at different levels of contrast and luminance.

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2 Related Works

On the one hand, contrast can be roughly described as a ratio between different luminances. Its behavior is most of the time associated to thresholds over which a person is able to distringuish a target in a background and under which the same person cannot distinguish the target. Although the generally accepted threshold value is of 1% of the background luminance, there exists numerous methods to mesure the value of the threshold and many applications [4].

On the other hand, luminance is described in photometry as the luminous intensity emerging from a surface and converging to the eye. Based on its value, it can belong to the photopic field ($L < 0.001\ cd/m^2$), the scotopic field ($L > 10\ cd/m^2$) or the mesopic field ($0.001 < L < 10\ cd/m^2$).

Rose [5], in 1948, published one of the first works that tried to evaluate performance on a absolute scale. Rose tied contrast, luminance and size in a single formula (Eq. 1) where α is the size of the object to be seen, L the luminance of the object and C the contrast of the object with respect to the background. k is a constant member that can be computed with other parameters.

$$\alpha \times L \times C^2 = k \tag{1}$$

While the Rose model gives a very good approximation of a Bayesian ideal observer, it has a limited range of validity. Hence, Burgess [6] revisited it to serve image quality purposes. Progresses were made on the model toward the limitation of the performance by the noise of the input signal.

Though, as it appears that there exists a contrast value beyond which performance diminishes, the single threshold contrast value seems not to be enough. Following this idea, the International Commission for Eclairage (ICE), through H. R. Blackwell [7], designed a model of visual performance. The approach is to specify a level of performance based on a visual task's lighting parameters such as its luminance and contrast and thus establish task lighting standards. The model first compute a level of visibility in which the task is performed and then rate the overall performance. The entry parameters of the model are the difficulty of the task, the age of the observer and the lighting parameters. Its range is quite consequent as it takes a luminance from 1 to 10000 cd/m^2 but only works for eccentricities lesser than 3 degrees. One main drawback of the model is that it should not be used in interior lighting as light is then mostly directional and specular.

However, the CIE model is only an enhanced contrast threshold model: suprathreshold values are obtained through multiplying the threshold by a constant (the visibility level). That's why Rea [8], [9] proposed a bit later its own model of visual performance (RVP) that provides results similar to other studies measuring suprathreshold behavior. Rea goals were to build a suprathreshold visual performance model that would be independent of task performance and consistent with the literature. His model is based on the compression effect that was theoretized out by Naka and Rushton in 1966 and Lipetz in 1969 as a self-shunting mechanism. The compression effect implies that at some point, despite increasing the magnitude of a stimulus, the sensation magnitude will not increase. The compression effect is described in the following equation (Eq. 2) with R the response, R_{max} the maximal response, I the stimulus intensity, n an exponent and K the stimulus intensity producing half of the maximum response.

$$\frac{R}{R_{max}} = \frac{I^n}{I^n + K^n} \tag{2}$$

In a second time, Rea and Ouellette expanded Rea's RVP model with a reaction time experiment [10]. They built a model that can predict the reaction time to performing a vision task. The difference between reaction times in given conditions of luminance and contrast and a reference reaction time can then be linked to a RVP value. Later on, Rea and Ouellette enhanced their model to add the influence of aging [11].

Last but not least, enhancement propositions of Rea's model were made by Kambich [12] in 1991 and O'donell *et al.* 20 years later [13]. For Kambisch, though the model is a valuable tool based on robust data, the size and contrast treatments have weak theoretical bases. Kambich replace then the sole contrast measure by three stages modeled on vision models: linear filtering, non-linear filtering and pooling stage. His model does not however consider adaptation luminance. O'donell *et al.*, on their side, showed that the addition of color in the model of RVP can significantly raise the performance level. Luminance and color are both important in the treatment process of the image by the brain. However, the importance of the color is related to the amount of contrast: the lower, the most important the color is. Under contrast values of 0.20, color can be used to help performance, while for contrast values over 0.6 the sole luminance drives the performance.

In our study, we decided to focus on Rea and Ouellette's model, without taking into account enhancement proposed by Kambich and O'donell *et al.*. The point is to validate the reaction time predictions, through an experimentation, that can be computed through Rea and Ouellette model. The validation or invalidation would allow us to say whether the RVP model is fitted for virtual reality or not.

3 Apparatus

Since we want to evaluate the validity of Rea's model in Virtual Reality (VR), we came with an experiment protocol somewhat close to his. However, some hypotheses and adaptations were necessary (*see below*).

The experiment took place in a 4 faces CAVE-like display system and involved 32 subjects: 23 males and 9 females between the age of 20 and 27 years (mean = 25, sd = 1.8). The population is described in Fig. 2. The CAVE-like display system specifications are given in the following table (Table 1). The subjects were seated in a car seat and positioned for their eyes to be 2 meters away from the front face. They were not wearing any 3D-stereoscopic glasses and the experiment was carried out with monoscopic images. They also had the instruction to keep the head still in the head-support.

Table 1
Dimensions of the CAVE-like immersive VR system

Face	Physical size	Display resolution
Front	3.60 x 2.70 m	1600 x 1200 px
Left	4.20 x 2.70 m	1920 x 1200 px
Right	4.20 x 2.70 m	1920 x 1200 px
Floor	4.20 x 2.70 m	1600 x 1200 px

The whole 4 faces were displaying a unique grey color (the background color). No other lights were lit in the room, the CAVE-like display system screens were hence the only source of light. The background color was varying between 5 values during the experiment in order to change the amount of light arriving to the eyes of the subjects. The values and their associated luminance can be found in Table 2.

Table 2
Relation between background color and background luminance - Number of trials/contrasts per subject for each background luminance

RGB Code	Luminance	N. of trials
(0,0,0)	0.07 cd/m^2	13
(32,32,32)	0.41 cd/m^2	22
(80,80,80)	3.74 cd/m^2	26
(128,128,128)	11.72 cd/m^2	26
(176,176,176)	23.18 cd/m^2	20
(255,255,255)	42.90 cd/m^2	13

A stimulus shaped as a 2cm-wide disk was appearing at random timings at the center of the front face. The subjects had to press the A button on a Xbox360 controller they held in their hands as soon as they perceived the stimulus. Doing so, we could measure their reaction times. The color of the stimulus was varying over different pre-calculated levels of grey to achieve certain amounts of contrast. The experiment is hence not ecological.

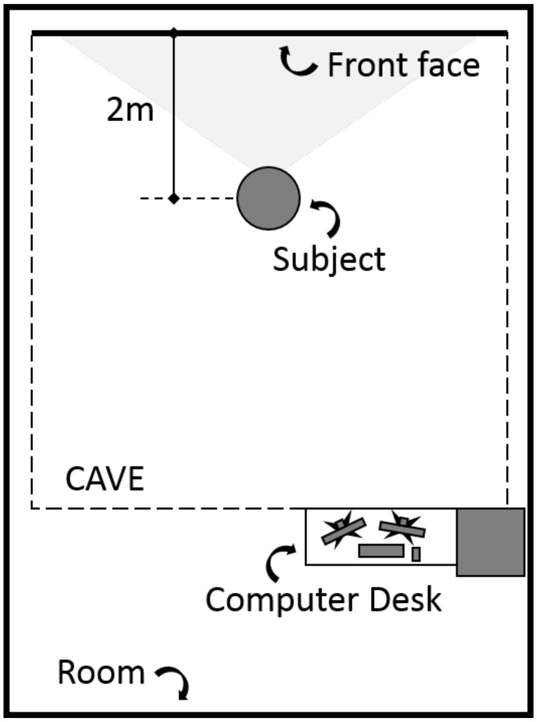

Figure 1. Top view of the implantation of the CAVE-like display system in the room.

In order to be able to predict what levels of gray should be used to display a specific amount of contrast for a given background luminance, we carried out a preliminary set of measures. First, all screens were lit in plain level of gray. Varying the level of gray, we measured the luminance emitted. We hence could plot the transfer function of RGB code toward luminance which equation was found with a least squared regression (Eq. 3). Similarly, on chosen background luminances (those used in the experiment) we displayed the target and made its level of gray vary and took measures of its luminance aswell. Another equation, for the luminance of task with respect to its RGB code, was then extracted with a least squared regression (Eq. 4). x represents the RGB code value which is the same for the R, G and B components as we are only working on levels of gray. The Maple software from Maplesoft was used for the regressions. The measures were made with a Konica-Minolta Chroma Meter CS-100. All the measures and afterwards the experiment were conducted after a 1 hour warm up of the projectors as recommended by the CIE (IEC 61966-6:2005).

$$L_{bck}(x) = -65.5x^4 + 90.1x^3 + 19.7x^2 - 1.3x + 0.1 \quad (3)$$

$$L_{tgt}(x) = -26.1x^4 + 38.3x^3 + 3.7x^2 - 0.03x + 0.02 \quad (4)$$

The constrast is originally computed in Rea's experiment like in Eq. 5. We make the hypothesis that the adaptation luminance (L_a), which is the total luminance which arrives to the eye, is equal to the the luminance from the screens (background luminance, L_B). In other words, we say that since the screens are the only source of light in the room, the adaptation luminance is the luminance emerging from the screens.

$$C = \frac{T|L_B - L_T|}{L_a} \quad (5)$$

Rea and Ouellette used a neural filter of transmitance T to pilot their contrast value: they would reduced the perceived contrast by densifying the neural filter in front of the eye. Plus, they used a small light directed toward the eye with a beam splitter to add on command a veiling light to reduce perceived contrast. Since we pilot our contrast directly on the screen by changing the color of the task depending of the background, we did not use any filter and can then always set the transmitance value to $T = 1$. Hence, with both hypotheses, we came with our own contrast equation (Eq. 6). Both equations only works when the background is more luminous than the task ($L_B \geq L_T$) allowing to compute contrast values by lower value only. We hence use a slightly modified version of the equation to compute contrast values by greater value (Eq. 6).

$$C = \frac{|L_B - L_T|}{L_B} \; and \; C = \frac{|L_B - L_T|}{L_T} \quad (6)$$

The subject was first invited to sit in the car seat and then introduced to his task (stimulus detection and reaction time measurement). The experiment was unfolding as follow: a background luminance was set. When the subject felt ready, s-he could launch the apparitions of the targets by pressing another button on the controller. When the sequence was launched, targets appeared successively with a random time between each. The target contrast relative to the background were specifically chosen to produce a desired contrast. The subject had then to wait for 3 to 5 minutes so that his-her eyes accommodate to the new luminance. The targets level of gray was chosen with great care to achieve precise amount of contrast: 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90 and 1. The contrast values were achieved, when possible, by target color brighter and darker than the background. Hence, the number of trial per luminance is different as for some background luminances some contrast values (either by brighter or darker value) were not possible. For example, when displaying a full black color (RGB Code = (0,0,0)) on the screens, it was not possible to have contrast values for the target by darker levels of gray. The order of contrast appearance was different for every subject as we used the Fisher-Yates shuffle to randomly sort it. When finishing a sequence at a given background luminance, the background luminance was changed to another one and the same process (wait for 3 to 5 minutes and then launch sequence when ready) was repeated. Similarly, the order of background luminance was randomly chosen for every subjects. The subjects got 6 non-measured trials before the beginning of the experiment to get used to it. The 6 trials were done at a luminance that would no be used during the normal experiment.

For a better understanding, the flowchart of the unfolding of the whole experiment can be found in Fig. 3. The "TARGETS" sub-flowchart that manages the apparition of the targets for a given background is detailed in Fig. 4. For each of the 6 background luminances (see Table 2), there is a

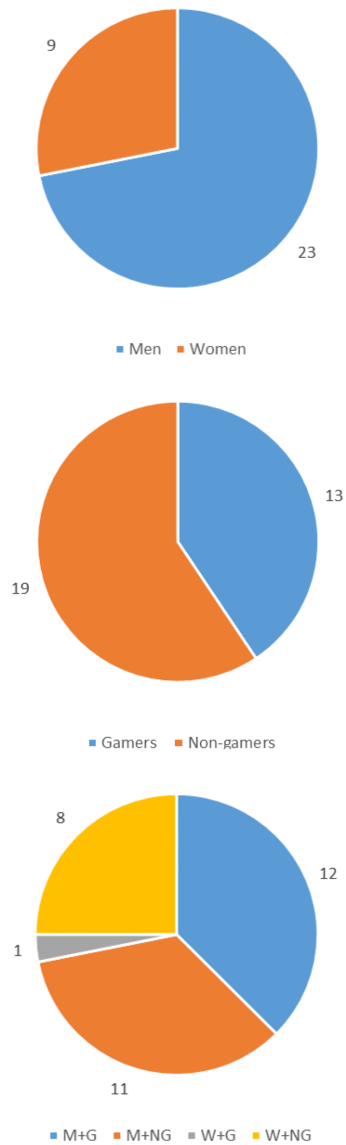

Figure 2. Distribution of the population between men (M), women (W), whether they consider themselves gamer (G) or not (NG) and the combination of the two.

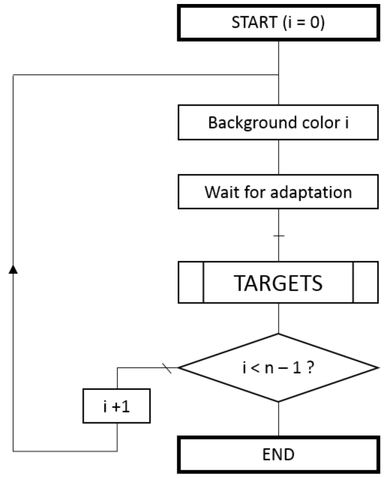

Figure 3. Flowchart of the unfolding of the experiment for a subject. The TARGETS sub-flowchart is described in an other figure.

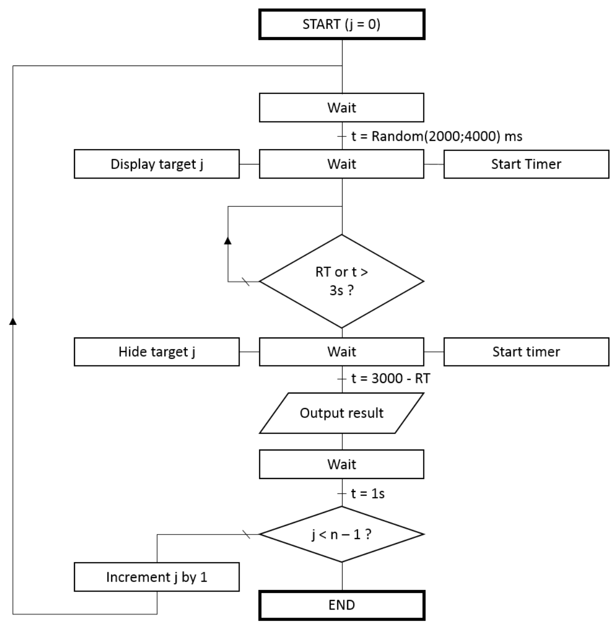

Figure 4. Flowchart of the unfolding of a sequence of targets appearances, for a given background luminance.

different number of displayable contrasts values (see Table 2).

4 Results

As we want to compare theoretical and measured reaction times, we first computed the predictions of Rea and Ouellette's model. Theses values can be found in Fig. 5. The values out of range of the model (which predicts that one should not be able to distinguish the target over the background and hence does not provide a reaction time value) are listed with an "x".

Some theoretical values such as $25432\ ms$ or $10865\ ms$ of predicted reaction time can seem rather important. Those come from a division in the model where the divider is very close to 0 (at least much closer than in the other cases) and hence the result races up very quickly.

The averaged measured reaction times values of the 32 subjects are listed in Fig. 6 with their corresponding standard deviations. Since the population is over 30 subjects, the Pearson standard deviation was used.

Measured values range from $371\ ms$ to $670\ ms$ with a mean value (of the means, excluding the diverging value, *see afterwards*) of $437\ ms$ (SD = $53\ ms$) and a mean standard deviation of $96\ ms$ (SD = $82\ ms$). A particular value ($2013\ ms$ for a constrast of 0.05 and a background luminance of $0.41\ cd/m^2$) can be highlighted.

The performance R is defined as the inverse of the reaction time RT: $R = 1/RT$. It is used instead of the reaction time to characterize the performance of a subject. The performance hence increases when the reaction time decreases and decreases when the reaction time increases. Fig. 7 shows an example of the graph of both theoretical and measured performances in the reaction time experiment. The example

Theoretical predictions (in ms)						
C\L	0.07	0.41	3.74	11.72	23.18	42.9
0.05	x	x	x	x	x	x
0.1	x	x	x	x	x	x
0.15	x	x	x	x	10865	3594
0.2	x	x	25435	1924	1429	1212
0.25	x	x	1686	1041	912	839
0.3	x	x	1039	788	725	685
0.4	x	2663	696	596	568	549
0.5	x	1272	577	517	499	486
0.6	x	929	517	473	459	449
0.7	x	773	481	446	434	425
0.8	4451	684	456	426	416	409
0.9	2448	626	439	412	403	396
1	1770	585	425	402	393	387

L in cd/m^2
C clamped between 0 and 1, by definition
x not distinguishable, below the threshold

Figure 5. Theoretical predictions for reaction times through Rea and Ouellette model.

is taken for a background luminance of $23.18\ cd/m^2$. The x-axis represents the different values of contrast, clamped by definition between 0 and 1. The y-axis represents the performance R, inverse of the reaction time (in ms^{-1}). The two first values of the predicted performance are below the threshold and out of range of the model. They are hence set to 0 which would be equivalent to an infinite reaction time and thus a lack of reaction.

5 Discussion

The first outcome that strikes is while Rea's model predicts some task that should not be seen (values below the threshold and out of the range of the model), the subjects saw all the tasks that were proposed to them, at all the lighting (background luminance and task contrast) conditions.

Secondly, there exists a major difference in behavior between theoretical predictions and subjects measurements. When the performance of the first one, at a given background luminance, increases with the contrast the latter is always sort of constant. The subjects had a similar performance on all the targets. Their reaction times were somewhat identical in lighting conditions however very different. Following the predictions of the model of Rea and Ouellette our subjects should not have been that potent. They should first not be able to see the target and then, when the contrast increases, become better and better.

At the end of the day, our results do not match at all with the predictions of Rea and Ouellette's model but still converge toward it for high contrast values. We tried our best to translate Rea and Ouellette's experiment to Virtual Reality. Though there are still fundamental differences that exist and that may explain the differences between predictions and measurements.

The major difference is the quantity of light and the quantity of light sources. In the Rea and Ouellette experiment, the only sources of light were a little screen $1.68\ m$ away from the user and a light that is directed toward the eye through a beam splitter. On top of that, the quantity of light was controlled with a neural density filter in front of the eye. On our side, the light come from giant screens surrounding the user with multiple indirect sources of light: projectors emit light towards the screens. No light-s were directly pointed toward the eye from a short distance and no neural density filter was used as we could more easily pilot the contrast and background luminance with the projectors only. Plus, Rea and Ouellette used a filter that is not directly fitted on the eye and hence let pass small amounts of light around it to the eye.

Average measured reaction time (in ms)						
C\L	0.07	0.41	3.74	11.72	23.18	42.9
0.05	465	2013	670	572	500	450
0.1	474	663	450	421	434	406
0.15	474	553	439	421	434	404
0.2	468	531	418	422	407	432
0.25	465	479	415	401	414	398
0.3	475	507	423	399	412	393
0.4	443	457	451	400	406	396
0.5	440	461	418	409	394	415
0.6	440	451	405	396	403	402
0.7	466	450	416	394	408	390
0.8	432	443	402	405	394	398
0.9	464	440	404	402	400	399
1	448	426	403	401	398	371

Standard deviation of average measured reaction time						
C\L	0.07	0.41	3.74	11.72	23.18	42.9
0.05	58	429	112	314	290	155
0.1	98	447	86	66	71	50
0.15	85	286	78	85	99	48
0.2	67	323	48	87	75	88
0.25	158	63	68	50	62	92
0.3	141	215	73	53	63	72
0.4	74	59	221	59	63	52
0.5	44	78	71	62	42	67
0.6	58	66	52	52	60	81
0.7	94	80	72	49	57	48
0.8	68	67	46	80	48	67
0.9	79	61	58	61	64	77
1	152	41	52	77	64	48

L in cd/m^2
C clamped between 0 and 1, by definition

Figure 6. Average and standard deviation of all reaction times for all lighting and contrast conditions.

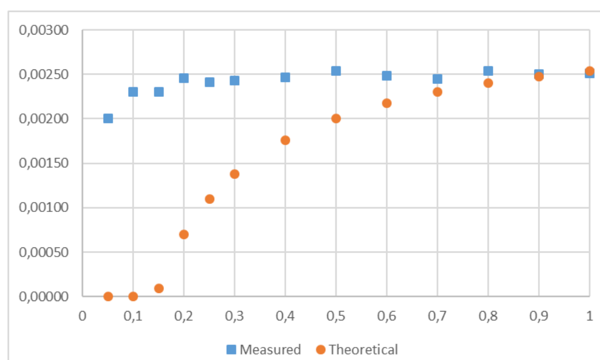

Figure 7. Graph of the predicted performances and the real measured performances in the reaction time task for a background luminance of $23.18\ cd/m^2$, viewing distance of $2\ meters$ and target size of $2\ cm$.

Hence, given the comparison between our results and the predictions of the model, in our opinion, Rea and Ouellette's model should not be used in Virtual Reality to determine the performance of the eye (with respect to the model of human vision) based on luminance and contrast.

6 Conclusion

The aim of the study was to be able to describe how much contrast and luminance one needs in Virtual Reality. Models already exists in the literature but none are applied to the specific field of Virtual Reality. The goal was to apply one of these models (Rea and Ouellette) in a VR context. An experiment similar to the one in Rea and Ouellette's papers was conducted in a CAVE-like immersive display system. We showed that, in our opinion, the RVP model is not fitted for Virtual Reality. Our results show a very distinct and opposite behavior from the predictions of the model. Reasons seem to come from the lighting conditions of Virtual Reality that are very different in quantity and nature from the conditions in which Rea and Ouellette conducted their own experiments.

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