Psychophysical Assessment of Perceptual Performance With Varying Display Frame Rates

Sihem Kime, Francesco Galluppi, Xavier Lagorce, Ryad B. Benosman, and Jean Lorenceau

***Abstract*—This study assesses the impact of display refresh rate on the perception of dynamic visual stimuli in humans. A projection platform was developed in that context, allowing control of the frame rate on a trial-by-trial basis. Using this display, we introduce a series of psychophysical experiments aimed to quantitatively assess objective perceptual performance at different frame rates. Tasks that are often implicitly performed when watching movies on a television set, or when wearing a head mounted display, were chosen: speed discrimination, spatial discrimination, and reading abilities, with stimuli undergoing horizontal motion in a wide range of speeds (16–38 deg/s). The results show that whatever the stimuli or the task, performance is significantly better at high frame rate (HFR) compared to 60 Hz, providing clear-cut evidence that low refresh rates limit the ability to reliably analyze moving stimuli. These results extend those of previous psychophysical experiments performed at low refresh rates, further characterize genuine visual performance in humans and provide an objective benchmarking methodology allowing to assess visual performance with a variety of displays. Results indicate that for low resolution displays, where increasing spatial resolution is not an option, increasing frame rate could benefit motion perception. We discuss these results and their implications with regards to current and emerging categories of visual displays, such as head mounted displays.**

***Index Terms*—Apparent motion, high frame-rate display, motion perception.**

I. Introduction

SINCE the 19th century, apparent motion has been extensively studied to evaluate the necessary frame rate to obtain a perceptually smooth motion as close as possible to that found in natural scenes. This paper quantifies the impact of high refresh rates on visual perception on three main modalities: speed discrimination, spatial resolution and pattern recognition. Conventional frame rates (25–60 Hz) are known to degrade visual perception when dealing with dynamic scenes. We show that increasing spatial resolution to improve visual perception alone is not sufficient, if not combined with higher frame rates which are currently becoming more accessible.

A BBC technical report [1] discusses how the benefits of increased spatial resolution are severely limited when using a low frame rate, particularly when moving cameras are involved. This can happen for instance during filming of sport events, or when doing point of view shots. Moreover, low frame-rate does not only impair rendering in high-resolution displays. The BBC report also insists its effects on panning cameras: these are even more concerned when using wearable displays, where the capturing device is constantly moving along with the head. This limitation applies both to augmented reality devices, where projected information is overlaid onto a natural scene, and to fully-immersive virtual reality devices. Recent reports indicate that image quality of broadcast television is notably degraded whenever a sequence contains motion above 10 deg/s: Toshiyuki *et al.* have characterized viewing conditions and statistical properties of TV broadcast in Japan [2]. They report that in sequences containing motion above 10 deg/s the image quality is worsened due to blur. While $\approx 40\%$ of the fastest moving object lies in the 0–10 deg/s range, another $\approx 50\%$ lies in the 10–40 deg/s range (Fig. 9 in [2]).

These concerns do not only apply to static displays for television broadcasting. When thinking of head-mounted displays, higher temporal resolution can be beneficial when moving the head or tracking moving objects. The Oculus Rift company [3] reports 75 fps as the minimum frame rate required to avoid flicker perception. Lower frame rates introduce discomfort when using their virtual reality technology. Their last prototype, the *Oculus Rift Crescent Bay*, is targeting 90 fps as a minimum frame rate.

The constantly renewing of display technologies calls for evaluations of the real impact of their innovative, and often-costly characteristics on human vision. To that aim, researchers often use subjective evaluations based on subjective ratings or on questionnaires. However, objective measures from psychophysics may be better suited to benchmark human performance, in particular when subjective evaluation is unreliable or difficult. Quantitative psychophysics further allow direct objective comparisons between different displays and between studies.

Recently, Kuroki *et al.* [4] evaluated the influence of high frame rates on image quality using movies recorded by a 1000 fps camera. After re-sampling these movies to obtain five

Manuscript received April 20, 2016; revised June 29, 2016; accepted August 4, 2016. Date of publication September 2, 2016; date of current version October 11, 2016. This work was performed in the frame of the LABEX LIFESENSES [ANR-10-LABX-65] and was supported by French state funds managed by the ANR within the Investissements d'Avenir programme [ANR-11-IDEX-0004-02]. The work of F. Galluppi was supported by GenSight Biologics. The work of S. Kime was supported by Alten SA (CIFRE no. 2011/1342). The work of X. Lagorce was supported by the European Union Seventh Framework Programme (FP7/2007-2013) under Grant 604102 (HBP). The work of J. Lorenceau was supported by ANR-10-LABX-0087 IEC and ANR-10-IDEX-0001-02 PSLPSL*.

S. Kime, F. Galluppi, X. Lagorce, and R. B. Benosman are with the Department of Vision and natural computation, Sorbonne Universités, UPMC Univ Paris 06, UMR S 968 INSERM U968, Institut de la Vision, Paris 75012, France (e-mail: sihem.kime@inserm.fr; francesco.galluppi@inserm.fr; xavier.lagorce@crans.org; ryad.benosman@upmc.fr).

J. Lorenceau is with the Laboratoire des Systèmes perceptifs, Département d'Etude Cognitive UMR 8248 CNRS-ENS, PSL*, Paris 75005, France (e-mail: jean.lorenceau@ens.fr; http://www.cognition.ens.fr).

This paper has supplementary downloadable material available at http://ieeexplore.ieee.org.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JDT.2016.2603222

different frame rates ranging between 60 Hz and 480 Hz, they asked participants to subjectively evaluate the degradation of perceived motion compared to 480 Hz projections on a scale from 1 (very annoying) to 5 (imperceptible). They found that a 250 Hz frame rate allowed avoiding perceived blur and jerkiness, without changes in perceived quality above this frequency.

Subsequently, Kuroki [5] assessed the impact of high-frame rate projection on 3D perception, by projecting random dots stereograms with different amount of disparity. Asking participants to judge the depth of a test pattern compared to the reference pattern, they found that participants best discriminated depth information at 240 Hz. Hoffman *et al.* [6] studied motion distortions and perceived depth in stereo vision, by emulating the characteristics of LCD and DLP displays using a 200 Hz CRT monitor. Participants were asked to report flickering, motion artifacts (also in depth) and depth distortion. They report that motion artifacts occur as the stimulus speed increases and the capture frequency decreases. Emoto *et al.* [7] used a questionnaire (ranking from 1 to 4) to investigate the quality of moving stimuli as a function of frame rate. Their results show a subjective improvement of motion quality between 60 Hz and 240 Hz of almost 1 point. They also report that the interaction between angular velocity and frame rate does not affect the quality of motion.

In this study, we use psychophysical methods to quantify the impacts of frame rate on speed discrimination, counting and reading moving stimuli. This way, we provide objective and replicable measures that reflect the effects of frame rate on perception. To get precise control on frame rate, we developed a platform based on a Digital Micromirror Device (DMD) capable of displaying binary sequences of images up to 1000 fps. DMDs have previously been used to study human perception. Deffner (1995) [8] use a DMD device along with an eye-tracker to assess the visual quality of images, by controlling parameters such as color saturation, brightness, texture fidelity etc. Saika *et al.* [9], also proposed a device based on a DMD to study phenomena that require precise spectrum control as in color-matching experiments. We used this platform together with moving stimuli, and designed psychophysical protocols to probe speed discrimination, spatial discrimination and digit identification as a function of frame rate. In the following, we first detail the platform characteristics and the protocols before presenting the experimental results.

II. Materials and Methods

A. Participants

A total of 13 participants took part in this study (11 males). Five individuals aged from 26 to 33 years old (mean age 29 ± 2.8) participated to the first experiment. Seven participants aged from 21 to 32 years old (mean age 26 ± 3.5) participated in the second experiment. Six individuals, aging from 27 to 38 (mean age 29 ± 4.1) took part in the third experiment. Two participants participated in all experiments while one only in 2 experiments (task 2 and 3). All participants had normal, or corrected to normal, vision. During the experiments participants were positioned at 140 cm from the screen and had their head maintained by a chin rest.

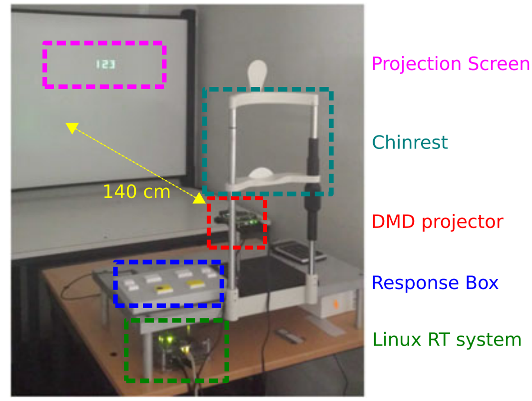


Fig. 1. Experimental setup: the stimulation platform consists of a TI DLP3000 DMD projector controlled by a real-time embedded Linux system. Participants were positioned 140 cm from the screen, with their head maintained by a chinrest, and provided their responses using a response box.

B. Stimulation Platform

To compare performance in visual tasks while changing the frame rate on a trial-by-trial basis, we developed a stimulation platform capable of rapidly switching between different frame rates in a precisely controlled way (see Fig. 1). We used a Texas Instrument LightCrafter projector controlling a DLP3000 Digital Micromirror Device (DMD) [10] to generate moving stimuli at 60 Hz or 1000 Hz. The DMD comprises an array of mirrors that can rapidly switch between two discrete angular positions (-12° and 12°) to enable or disable the reflection of a light source on a screen [11]. The DLP3000 is composed of an array of 608×684 mirrors tilted by 45 degrees; in order to avoid artifacts which might be introduced by the native addressing scheme of the DMD, we adopt an alternative one described in the supplementary material. The DMD was controlled with a real-time embedded Linux system based on an OMAP 4460 CPU, with bespoke software enabling the control of any mirror independently (e.g. no need to send the whole image) with a millisecond precision. The duration of the on-position of each mirror is configurable, which permits to keep a mirror on for long durations (up to 700 ms) without re-sending any command to the device, thereby significantly reducing the bandwidth required to operate the system. Conversely, the mirrors can be independently turned on and off with a minimum time step of 0.7 ms. Thus, this platform allows the generation of visual stimuli using different frame rates in a very rapid, bandwidth efficient way. While the DLP3000 system can in principle provide binary stimulation up to 1440 Hz, we limited the refresh rate to 1000 Hz to ease the communication between the controlling system and the DMD. Light intensity was encoded in two binary values, corresponding to a mirror being on or off. To ensure that the same amount of light enters the eyes at all frame rates, and to eliminate effects induced by different amounts of radiation across conditions, we used a duty cycle of 70%, corresponding to mirrors being turned on for 70% of the frame time.

Moving stimuli were displayed at integral number of pixel displacements, with all vertically aligned pixels changing at the same time for each frame rate condition.

A screen 102 $\times$ 76 cm) displayed the stimuli onto an area spanning a visual angle of 16.3 deg (40×32 cm at 1.40 m) with

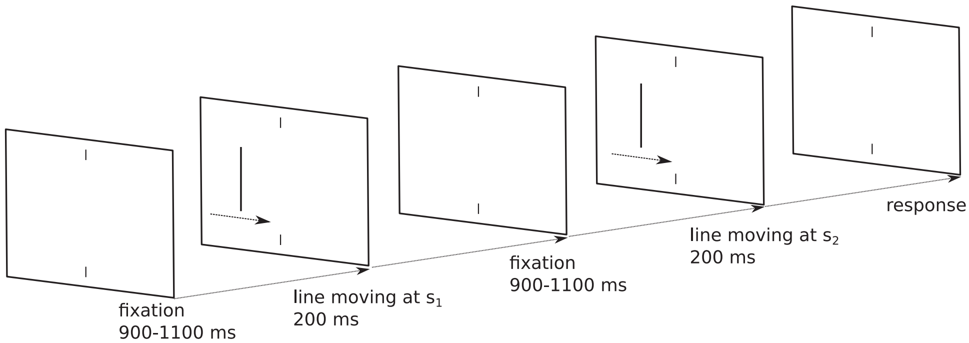


Fig. 2. Experimental paradigm for the speed discrimination experiment: a fixation point appeared for 1 ± 0.1 second, followed by a line moving at speed s_1 for 200 ms in a first temporal interval, followed by another fixation interval of the same duration, followed by a line moving at $s_2 \neq s_1$ for 200 ms. Participants were instructed to fixate the fixation point, and to report which of the two temporal intervals contained the fastest stimulus. The starting point of the stimuli, the time intervals and the direction of motion were randomized so as to avoid adaptation or predictive eye movements.

a QVGA resolution (340 × 240 pixels of 1.3 × 1.3 mm corresponding to 0.05 degree of visual angle at a distance of 140 cm). The stimuli (40 $\mathrm{cd/m^2}$) were projected in a dark room, with a light source of 530 nm wavelength against a dark background (9 $\mathrm{cd/m^2}$).

During the first and second experiments, responses were recorded using a Cedrus RB-834 Response Pad. Participants entered their responses through a USB keypad in the third experiment.

The device was driven in two modes during the experiments, either at 60 Hz or at 1000 Hz. Given the finite spatial resolution of our display, a change in the rendered position of the stimulus can only occur for a time allowing it to travel for at least 1 pixel. This effect leads to an effectively rendered frame rate which depends on the stimulus speed. For example, if a bar moves at a speed of 27 deg/sec, corresponding to .5 pixel per ms, it would effectively move every 2 ms even at 1000 Hz. Even with a higher frame rate, the effective frame rate would correspond to 500 Hz, with 2 ms being the minimum time needed for a bar to be displaced of at least 1 pixel. So, despite always setting the refresh rate at 1000 Hz, the effective frame rate varies accordingly to the stimulus dynamics. To avoid confusing the reader, we refer to these high frame rates as HFR (High-Frame Rate) throughout the rest of the paper, which corresponds to the maximum frame rate at which stimuli are rendered differently, as projecting at higher frame rates would not produce difference in rendering. In the case of the 60 Hz frame rate reference, we only update the position of the stimulation once per frame (every 16.6 ms). For clarity, we explicitly report the used and the effective rendered frame rate for every speed when describing the stimuli used during the experiments in the following sections.

III. Speed Discrimination

As stimuli in motion are affected by limited temporal resolution, we decided to investigate the effects of frame rate on the subjects ability to discriminate speed differences. To do so, we measure the ability of observers to assess small speed differences in moving objects using different frame rates. Our hypothesis is that, by increasing the frame rate, we can improve assessment of the speed of dynamic stimuli. Previous studies establish discrimination levels for speeds between 2 deg/s and 256 deg/s. McKee *et al.* found in [12], [13] that discrimination power in function of speeds followed a U-shaped curve with an improvement of speed discrimination between 2 deg/s and 50 deg/s. For higher speeds, above 64 deg/s, discrimination decreases [14]. Thus, in the range of speeds chosen for this experiment (16–37 deg/s), we expect to observe an improvement of performance between the slowest and fastest speeds. Although the idea that speed perception should be improved at a high frame rate compared to a low fame rate is not new, objective performance measures of the importance of this effect is, to our knowledge, lacking.

A. Stimuli and Procedure

Speed discrimination was estimated by projecting moving lines. The stimulus consisted of a line (Height: 240 pixels, 13 deg; width: 1 pixel, 0.05 deg), translating horizontally towards the left or to the right direction across the screen for a duration of 200 ms. This time interval is short enough to minimize intrusive eye movements [15], [16]; to further prevent anticipatory eye movements, stimuli randomly moved to the right or to the left.

Regarding the procedure, the time course of a trial (Fig. 2) was as follows: two fixation points, at the top and bottom of the screen, were presented for a random time (1 ± 0.1 sec). The stimulus then moved for 200 ms, followed, after a random delay (1 ± 0.1 sec), by a second stimulus moving for the same 200 ms duration. On each trial, the starting position was randomized so as to remove spatial and distance cues that could bias speed discrimination thresholds, as the distance traveled could be used as a proxy for speed. Participants were explicitly informed of this, so as to discourage them from using the stimulus arrival point as a strategy. They were instructed to fixate between the two points for the whole duration of the trial, and to indicated which of the two successive intervals contained the fastest motion (2 Interval Forced Choice, 2IFC).

In each block of trials (n = 160), a reference speed was randomly chosen amongst five speeds (Table I). The reference speed was shown on every trial with a random presentation order

TABLE I
REFERENCE AND TEST SPEEDS USED IN EXPERIMENT 1 AND ASSOCIATED HIGH FRAME RATE (HFR)

Reference speed (deg/sec)	Speed range ($\pm 12\%$)	Frame rates (Hz)	Max rendered frame rate (Hz)
16.2	14.3–18.1	60, 1000	300
21.6	19.0–24.2	60, 1000	400
27.0	23.8–30.2	60, 1000	500
32.4	28.5–36.3	60, 1000	600
37.8	33.3–42.3	60, 1000	700

Each experimental block used a fixed reference speed and uniformly random-drawn frame rates, difference between the test and reference speed, motion direction and presentation order. The test speed was randomly chosen with a difference in the [-12%, 12%] interval to the reference speed, by steps of 3%.

with respect to the test speed (2 Interval Forced Choice Procedure). The test speed was randomly chosen with a difference in the $[-12\%, 12\%]$ interval of the reference speed, by 3% steps. Importantly, the frame rate was randomly changed on each trial (either 60 Hz or HFR). Before each experimental block, participants were given 20 practice trials. Each session, corresponding to 5 blocks, lasted approximately 15 minutes. Therefore, the different conditions of the experiments were: the frame rate f (60 Hz or HFR), the 5 reference speeds s, and the 8 speed differences i of the test speed. Each condition was repeated 10 times, giving a total of $\mathrm{f} \times \mathrm{s} \times \mathrm{i} \times 10 = 800$ presentations. Table I summarizes the different reference and test speeds used in the experiment, and indicates the corresponding effective frame rates.

B. Results

Fig. 3 shows the percentage of correct responses for each reference speed as a function of the absolute speed difference. The 60 Hz condition is shown in red, and the HFR condition in blue. An analysis of variance indicates that performance is better for a high as compared to a low refresh rate $(1{,}198 = 27.61;\ \mathrm{p} < 0.001;\ \eta^2 = 0.12)$. Post-hoc analysis further showed that the effect of frame rate is not significantly different at the lowest speed tested (16.2 deg/s $\mathrm{F}_{1,38} = 0.036$; $\mathrm{p} = 0.852$), but significant ($p < 0.009$) for all other reference speeds (compare panel 1 with the other panels). Larger speed differences are discriminated more easily than smaller ones, as expected. Interestingly, the main effect of frame rate is found for the smallest speed differences (3% and 6%), pointing at increased discrimination capabilities when using higher frame rates. The difficulty in detecting the smallest speed differences can be accounted for this phenomenon, as they are closer to the perceptual thresholds. In this sense, discrimination capabilities can be defined as the smallest speed difference that a participant can correctly detect.

Figs. 4-5 summarize the effect of frame rate on speed discrimination. In Fig. 4, each curve represents the proportion of correct responses pooled across the different test speeds for each participant (dashed colored lines) as a function of the reference speed. Mean performance across participants is shown as a full black line. Results show an overall increase of correct responses with increasing speed, indicating that the effect of frame rate increases with speed.

We then computed a psychometric function for each speed (s), and determined the speed difference (Δs) corresponding to 75% of correct responses [Fig. 5(b)]. It can be seen that the Weber fraction $(\Delta s/s)$ for a 60 Hz frame rate is about 7%, which replicates previous results (e.g. [12]). In contrast, the Weber fraction is as low as a 3% for HFR, except at the lowest speed tested (16.7 deg/s). Overall, speed discrimination markedly improves with HFR displays, which is in line with our expectations.

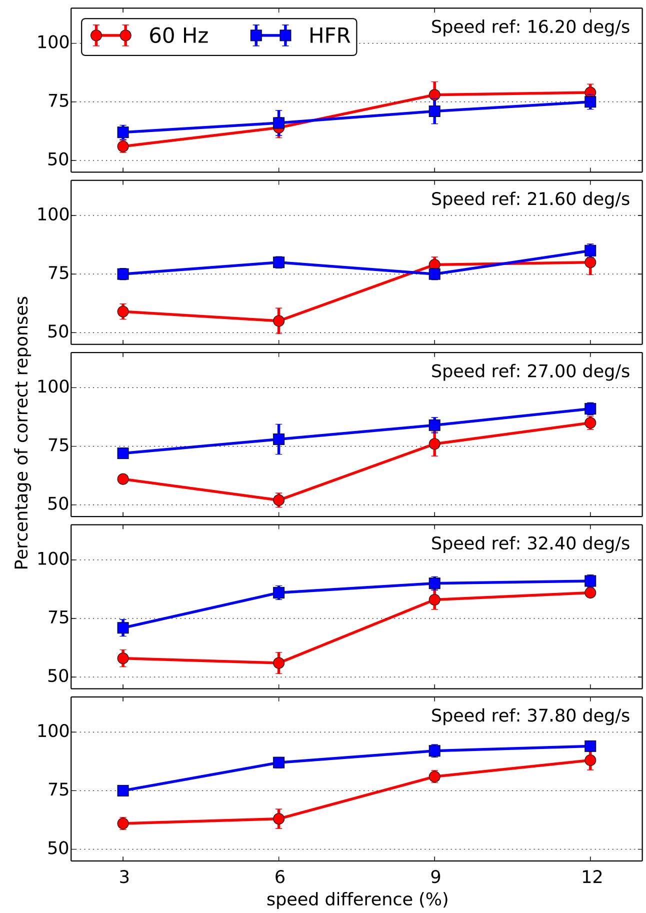


Fig. 3. Percentage of correct responses averaged accross participants for each reference speed as a function of speed differences (panels A-E); 60 Hz condition: red curve (round markers), HFR condition: blue curve (square markers). See text for details

IV. EFFECTS OF DUTY CYCLE

When several neighboring objects - e.g. parallel lines - move across a display screen, determining the number of moving

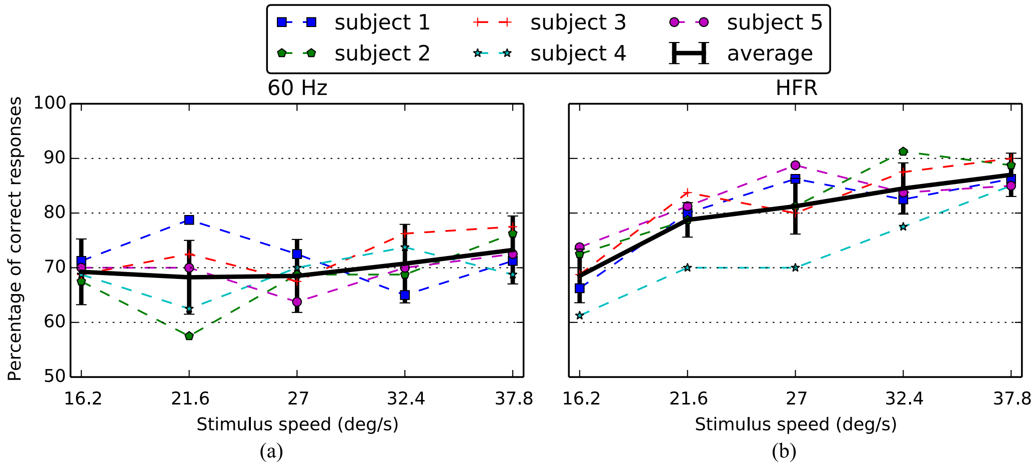


Fig. 4. Percentage of correct responses for different speeds and participants for the 60 Hz (left) and HFR (right) conditions; mean value and error bars are plotted in black. Performance is significantly better when projecting stimulation at HFR, and participants performance significantly improves with increasing speeds only in the HFR condition, matching our expectations regarding task difficulty.

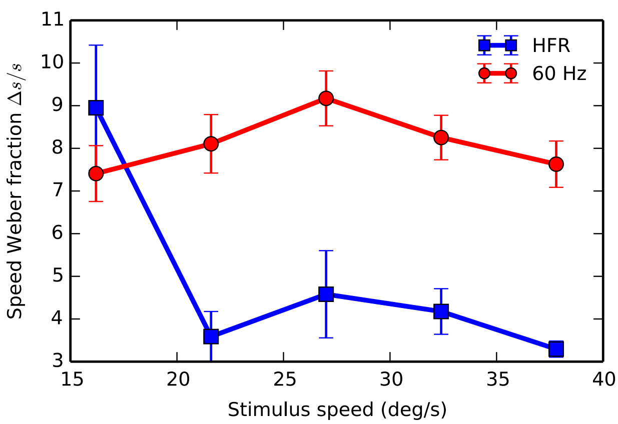


Fig. 5. Level of discrimination for the 2 frame rate conditions represented as a Weber fraction with threshold at 75%; 60 Hz condition: red curve (round markers), HFR condition: blue curve (square markers).

objects can be difficult at low (60 Hz) refresh rates, due to aliasing and visual persistence [17]. The objective of this second experiment is to confirm this hypothesis, by using a varying number of parallel lines with different spacing, moving at different speeds and asked participants to report whether the displayed objects were odd or even. This task was chosen because it requires counting the number of lines and mapping the response into a simple two alternative forced choice.

A. Stimuli and Procedure

The same setup as in Experiment 1 was used. The stimuli consisted of vertical parallel lines whose number varied from 2 to 5, with 4 different spacings (from 0.21 deg to 0.54 deg) between them (see Table II). Lines measured 2.9 deg in height and 0.05 deg (1 pixel) in width and moved horizontally across the screen for 420 ms with varying speeds (Table III). The experimental paradigm is outlined in Fig. 6(a). As in Experiment 1, the frame rate was randomly changed on each trial (either 60 Hz or HFR). Example of stimuli for different spacings and number of lines are presented in Fig. 6(b). Participants had to report if the number of lines was odd or even.

TABLE II
CONDITIONS OF SPACING DURING THE SPATIAL DISCRIMINATION EXPERIMENT: 4 DIFFERENT SPACING (FROM 0.21 DEG TO 0.54 DEG) BETWEEN LINES WHERE TESTED

Spacing distance (deg)
0.21
0.32
0.43
0.54

TABLE III
CONDITIONS DURING THE EXPERIMENT OF SPATIAL DISCRIMINATION: 5 DIFFERENT SPEEDS, IN THE RANGE 16.2–37.8 DEG/SEC AND 4 DIFFERENT SPACING (FROM 0.21 DEG TO 0.54 DEG) BETWEEN LINES WHERE TESTED

Ref speed (deg/sec)	Frame rates (Hz)	Max rendered FR (Hz)
16.2	60, 1000	300
21.6	60, 1000	400
27.0	60, 1000	500
32.4	60, 1000	600
37.8	60, 1000	700

Regarding the procedure, all participants were first trained with static lines to check their capability to correctly perform the task. Before each experimental block, participants further performed 15 trials with the different speeds, to familiarize with both the task and the moving stimuli. Fig. 6(a) depicts the time course of a trial: one second after the appearance of the fixation points, the stimuli were presented and moved across the screen. As the task cannot be reliably performed with central fixation, participants were instructed to pursue the target, so as to stabilize the stimulus on the fovea. Since the stimuli always had the same initial position, it was easy to predict the motion path, which facilitated stimulus tracking. Each experimental block

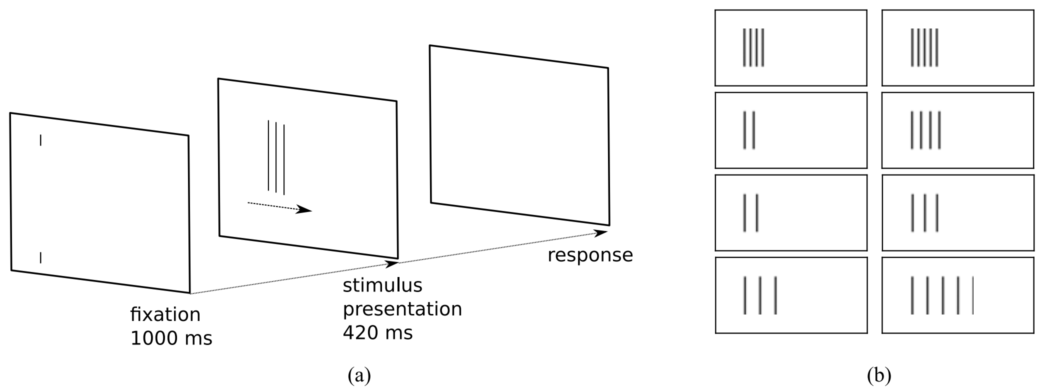


Fig. 6. (a) Experimental paradigm: after $1s$ of fixation, a set of lines started moving horizontally across the screen for 420 ms. Participants were asked to report if the number of presented lines was odd or even, and they were instructed to pursuit the stimulation. (b) Stimuli consisted in 2 to 5 vertical lines with different spacings (see Table II).

used a fixed reference speed, uniformly random-drawn frame rates and 2 repetitions of the same stimulus. Participants performed 2 blocks for each speed in order to collect 4 repetitions per stimulus and per participant (64 presentations per block, each block lasting approximately 5 minutes). The experimental parameters were therefore: the frame rate f (60 Hz or HFR), the 5 reference speeds s (16.2, 21.6, 27, 32.4 and 37.8 deg/s), the 4 spatial spacing between lines r (0.21, 0.32, 0.43, 0.54 deg of visual angle), and the 4 patterns b (2, 3, 4, 5 lines), giving a total 640 trials per participant. Participants tracking ability was evaluated in a separate experiment using a 100 Hz screen with an Eye-LinkII eye-tracker (sampling 500 Hz, SR Research Ldt.), by performing a simple tracking task with the same stimuli and speeds used in the main experiment. The eye-tracking evaluation was performed without other concurrent task. The time course of the pursuit eye-movements is as expected: after 100 to 200 msec, the participants make a catch-up saccade to foveate the stimulus, followed by a tracking phase with an average tracking error of $\approx$2 deg for 200–300 msec (during which the retinal motion is minimum). Each participant performed 20 trials per speed. The results (data not shown) indicate that all participants could track the stimuli, although pursuit was less accurate at high speeds.

B. Results

The percentage of correct responses, averaged across participants, is presented in Fig. 7. Performance is overall better at HFR compared to 60 Hz frame rate [Fig. 7(a) versus (b)]. At a low frame rate, averaged performance is overall less than 90%, decreases with increasing speeds, and is better for a large spacing between the lines. At a high frame rate, participants performed above 90% for all spacings and all speeds, with the exception of the smallest spacing and highest speed, for which performance drops to about 80% of correct answers. An ANOVA performed on these results confirms that performance is consistently better at a high, as compared to a low, frame rate ($F_{1,960} = 216$; $p < 0.001$, $\eta^2 = 0.18$). In addition, the difference in performance between frame rates increases with stimulus speed. The line spacing also affects visual performance of both refresh rates in

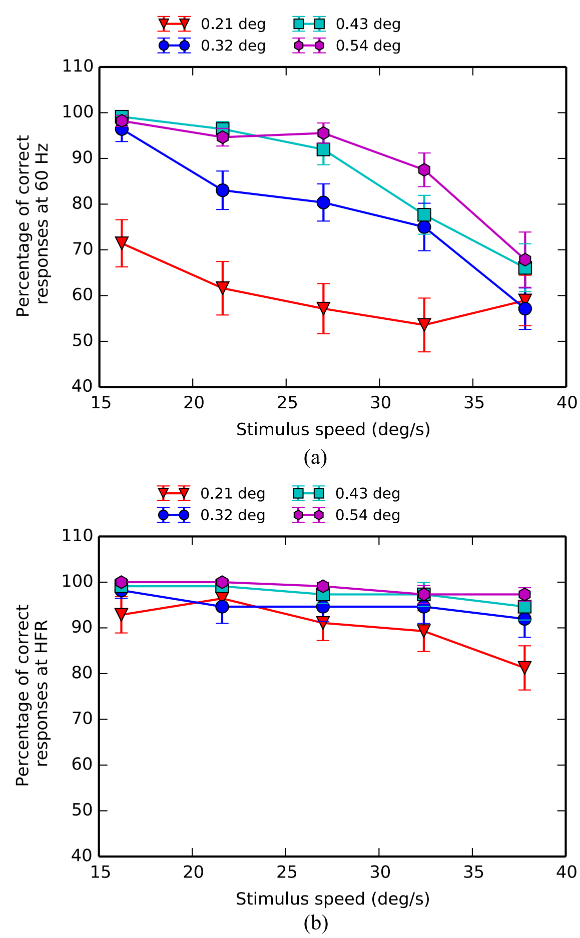


Fig. 7. Percentage of correct responses averaged across participants as a function of stimulus speed for the different spacing, at 60 Hz (a) and at HFR (b). Performance decreases markedly at 60 Hz as the speed of the stimuli increases, but remains high at HFR. Error bars represent inter-participants variability +/− SEM. See text for details.

a significant way ($F_{3,480} = 44.8$; $p < 0.001$, $\eta^2 = 0.22$ for 60 Hz and $F_{3,480} = 8.9$; $p < 0.001$, $\eta^2 = 0.05$ for HFR). A univariate variance analysis shows a significant interaction between speeds and frame rates ($F_{4,960} = 11$; $p < 0.001$, $\eta^2 = 0.04$), but not

TABLE IV
MINIMUM SPACING D_{lim} REQUIRED TO AVOID AN OVERLAP BETWEEN TWO LINES IN 2 SUCCESSIVE FRAMES AT 60 HZ, COMPUTED USING EQUATION (2)

Speed (deg/sec)	Minimum inter-line spacing (deg)
16.2	0.27
21.6	0.36
27.0	0.45
32.4	0.54
37.8	0.63

between speed and number of lines ($F_{12,960} = 0.3$; $p = 0.93$). A significant interaction between speed and spatial separation is only found for the 60 Hz conditions ($F_{12,480} = 2.1$; $p < 0.05$, $\eta^2 = 0.05$).

Although the results of this experiment are clear-cut and illustrate the strong effect of frame rate on the perception of moving stimuli, it would be useful to generalize which spatio-temporal characteristics of both humans and displays determine the visibility of moving stimuli. The general framework developed by Watson (2013) provides a way to analyze our results along these lines. Based on human psychophysics that characterized human visual sensitivity in the Fourier domain [18], [19], Watson defined a window of visibility in the Fourier space that provides means to analyze our results in a more general theoretical context [20]. Along with the window of visibility, Watson defines a critical frame rate F_{lim} (Hz) as the minimum temporal resolution needed to analyze a stimulus moving at a specific speed S_{stim} (deg/s) given a visual acuity A_{lim} (cycle/deg):

$$F_{\text{lim}} = S_{\text{stim}} \times A_{\text{lim}} \quad (1)$$

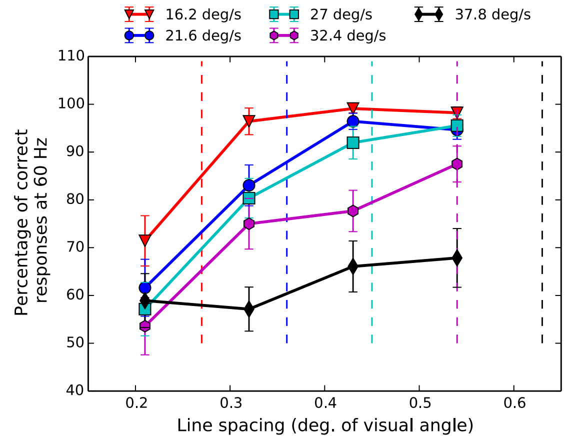
In the context of our experiment, we define the spatial limitation, A_{lim}, as the spacing between 2 lines (as human visual acuity is less than this value). The minimum spacing D_{lim} required to prevent the overlap of 2 lines in two successive frames is set by equation (2). D_{lim} depends on the frame rate (F_{display}) or temporal resolution ($T_{\text{display}} = F^{-1}_{\text{display}}$) and on the stimulus speed S_{object}:

$$D_{\text{lim}} = T_{\text{display}} \times S_{\text{object}} \quad (2)$$

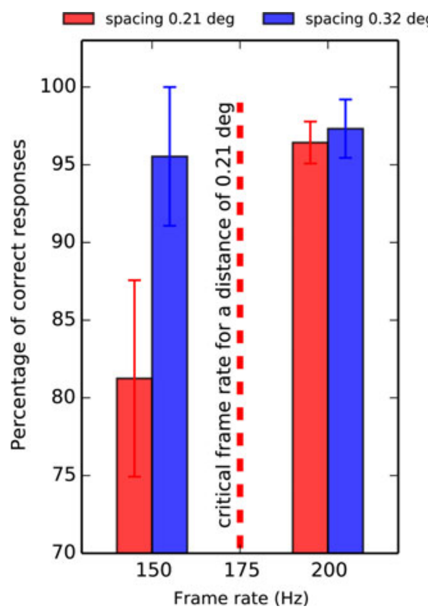
We computed the limit D_{lim} for each speed as a function of frame rate [Table IV and dashed line in Fig. 8(a)]. The minimum spacing D_{lim} decreases with increasing refresh rate.

In the present experimental conditions, if a movie is projected at 60 Hz, objects must move at a maximum speed of 2.9 deg/s to elicit "smooth" apparent motion and to avoid stimulus overlaps. The same calculation gives a maximum velocity of 49 deg/s for a 1000 Hz display.

For example, given a 0.21 deg (4 pixels) separation between lines and a speed of 37.8 deg/s, accordingly to Eq. (2) the refresh rate necessary to avoid overlapping in successive frames is 175 Hz. In order to verify this prediction, 2 participants performed the counting task at 150 Hz and 200 Hz. Results, reported in Fig. 8(b), show that at 150 Hz performance increases when the spatial separation increases from 0.21 deg to 0.32 deg (4 to 6 px). A T-Test confirmed significant difference in



(a)



(b)

Fig. 8. (a) Percentage of correct responses averaged across observers as a function of the spacing between lines for different speeds at 60 Hz. The color-coded dashed lines represent the spacing, D_{lim} [see Eq. (2)] between lines for each speed: if this spacing is smaller than D_{lim}, the perception of motion is impaired and performance drops. (b) Results of a control experiment illustrating the influence of frame rate and spacing on performance. Two spacing (0.21 and 0.32) and 2 frame rates (150 and 200 Hz) were used. The vertical dashed line shows the minimum frame rate (175 Hz) that permits to avoid a bar overlap in 2 successive frames for a speed of 37.8 deg/s with a spacing of 0.21 (red). As predicted, performance is poor at 150 Hz but dramatically improves at 200 Hz. With a spacing of 0.32 deg (blue), greater than S_{lim}, no such effect of frame rate is observed.

performance between 150 Hz and 200 Hz with 0.21 deg spacing ($T(7) = 2.4; p < 0.05$) and between a spacing of 0.21 deg and more for the 150 Hz condition ($T(8) = 2.4; p < 0.05$).

V. DIGIT IDENTIFICATION

The aim of the third experiment is to quantify performance in reading moving digits as a function of refresh rate. Such a situation occurs when trying to read a moving string of digits or characters on a static device displaying a moving stimulus,

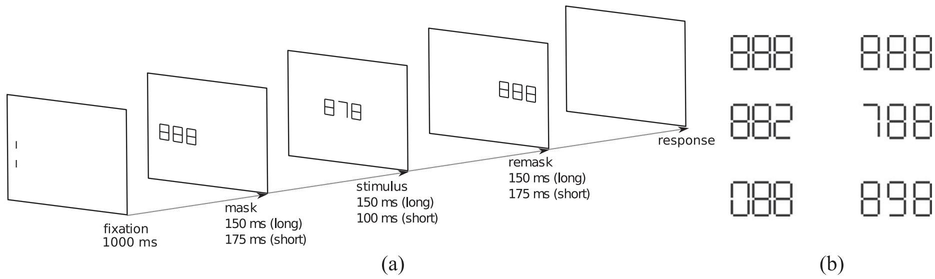


Fig. 9. Digit identification experiment: (a) after an initial fixation cue, pursuit tracking is initiated with a moving mask (three 8 digits); after 150 ms of motion (or 175 ms for the short duration condition), one of the three digits form the mask is turned into another digit which is masked again after the duration chosen for the trial (150 or 100 ms). Participants are instructed to track the stimulus and to report which digit was presented after the trial ends. (b) Mask (top) and examples of digits used during the experiment. Two spatial separations between digits were used: 0.05 deg (1 pixel, left) and 0.16 deg (3 pixels, right).

or when trying to read while using a head mounted display and moving the head.

A. *Stimuli and Procedure*

The setup used was the same as in Experiment 1. The stimuli consisted in strings of numbers made of 3 digits, presented against a white background, moving from left to right. The inter-digit spacing was either 0.05 or 0.16 deg and a single speed (32.4 deg/s) was used. All digits were coded with a maximum of seven segments (1 pixel width). They consisted in 30 $\times$ 15 pixels moving images (for the maximum inter-digit distance), corresponding to 3.9 $\times$ 2.1 cm on the projecting screen (each digit measured 8 $\times$ 15 pixels). Two masks consisting in three "8" characters, were used each corresponding to a different inter-digit spacing [Fig. 9(b), top].

Regarding the procedure, participants were asked to identify a single digit within a moving string of three digits. As this task can hardly be done if the eyes are static, tracking was facilitated by first presenting a moving mask. After 150 or 175 ms, a duration sufficient to initiate smooth eye tracking, one of the digits (different from the one used as a mask) was unmasked for a short period (100 or 150 ms) and masked again (for 150 or 175 ms), while motion speed was maintained constant during the whole trial. After motion ended, participants were asked to report which digit was presented. A diagram showing the time course of a trial is presented in Fig. 9(a). Before the experiment, participants (N = 6) were given 15 practice trials to familiarize with the task and the stimulation.

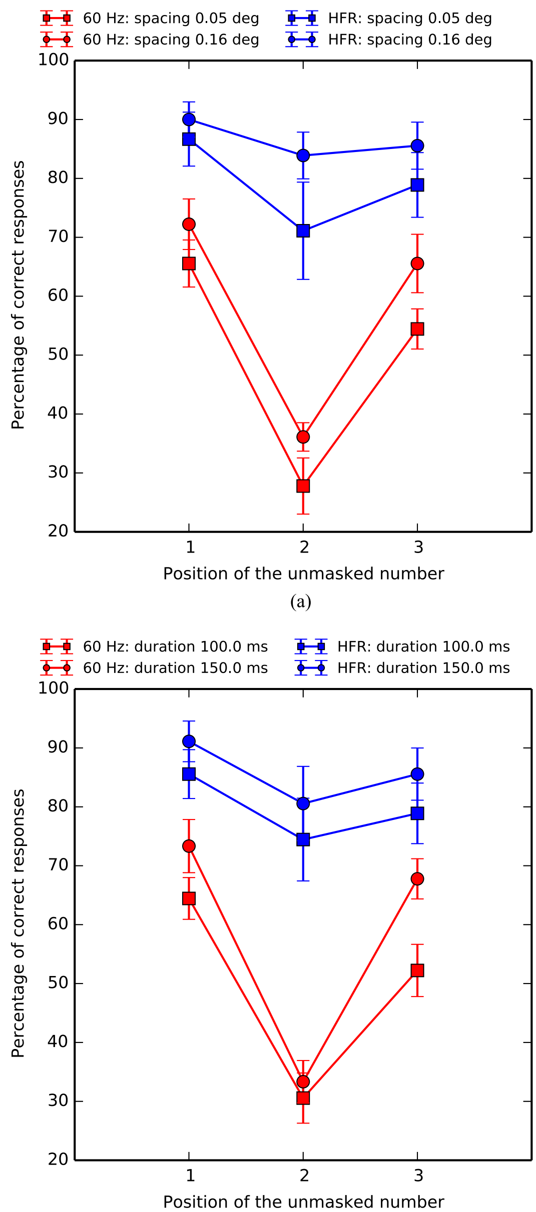
B. *Results*

The percentage of correct responses is plotted in Fig. 10. Performance is better for a high, as compared to a low, refresh rate, as confirmed by a one way ANOVA computed on the whole data set ($F_{1,120} = 107.8$; $p < 0.001$, $\eta^2 = 0.47$).

In addition to the frame rate effect, several other aspects of the results are worth noting. At 60 Hz, the position of the digit to identify within a string has a profound effect on performance, with digits in the middle position being hardly identified (note that chance level is 11%). For the other positions (digits left or right of the string), performance is much better than for the middle digit, although the right digit (position 1), corresponding to the leading edge of the string, appears to be identified more easily, but this effect is however only marginally significant ($F_{1,46} = 3.8$; $p = 0.056$). This position effect is much less at HFR and does not reach significance ($F_{2,60} = 1.94$; $p = 0.152$). The other variables, duration of unmasking of the string and inter-digit spacing, also influence performance, but to a lesser extent and with little differences between frame rates. As expected, performance is worse for a shorter 100 ms unmasking duration ($F_{1,120} = 7.4$; $p = 0.008$, $\eta^2 = 0.06$), and for a smaller spacing between digits ($F_{1,120} = 8.3$; $p = 0.005$, $\eta^2 = 0.07$). At 60 Hz, the large effect of the digit position within the string suggests that lateral masking and the partial overlap between moving digits account for the results, and underline the strong limiting effect of low frame rate for this type of tasks. To determine whether different digits elicit different performances, we computed a confusion matrix for the two different frame rates (Fig. 11). In this Figure, color intensity denotes classification accuracy. At HFR, most digits are correctly classified (82.7% on average), as all digits lie along the diagonal (only the digit "0" is misclassified, presumably because of the high similarity with the masking digit). At 60 Hz, a general drop in classification accuracy is observed, reaching only 53.7% on average. A closer look at this matrix suggests that the level of performance depends on the number of lines that are turned off to draw the digit to be identified. For instance, the digits "4" and "7" with best performance (76% and 70% respectively), have respectively 3 and 2 lines in common with the masking "8", while the digit "0" has 6 lines shared with an "8".

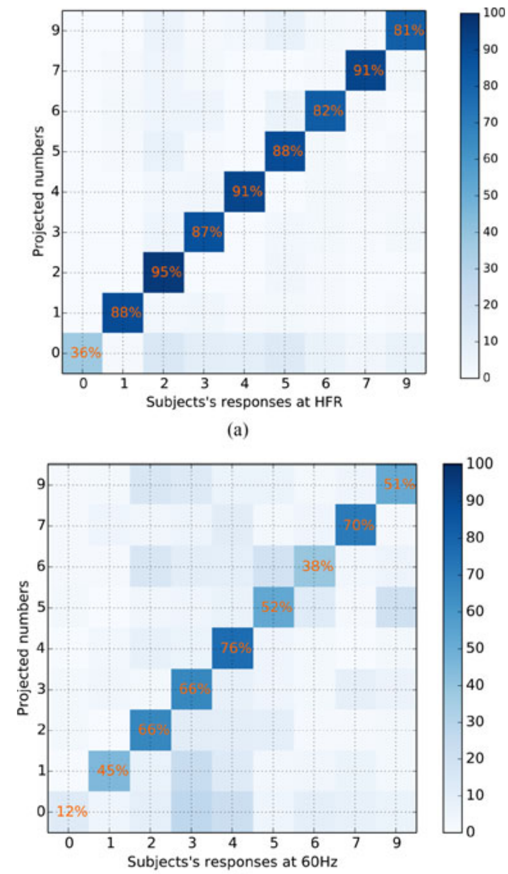
VI. Discussion

This study presented the results of three psychophysical experiments using objective forced choice protocols, designed to quantify the effects of display refresh rate on the perception of moving stimuli. All three experiments indicate, in agreement with previous results and model predictions, that perceptual judgments are degraded at a low, 60 Hz, refresh rate, as compared to a HFR. The perceptual differences related to refresh rate are more important at high stimulus speeds and occur during fixation as well as during pursuit eye movements. The different tasks were designed to evaluate different visual capabilities, that are performed, although sometimes implicitly, when watching movies or playing video games containing moving objects, or when using head mounted displays: speed discrimination, ob-



(b)

Fig. 10. Percentage of correct response in the digit identification experiment, averaged across participants, as a function of the position of the digits, for 2 frame rates, 2 spacing distance between digits. (a) 100 ms exposure, (b) 150 ms exposure. Digit identification performance is better at HFR, regardless of the position, the duration, or the spacing between digits. At 60 Hz, performance drops notably for digits in a middle of a string, as compared to other digit positions. The inter-digit spacing and the stimulus duration also impact performance. Note that chance level for this task is 11%. Error bars represent variability across participants +/− SEM. See text for details.



(b)

Fig. 11. Digit classification confusion matrix: color intensity denotes classification accuracy. At HFR, most digits are correctly classified, with only 0 being often misclassified. At 60 Hz, a general drop in classification accuracy is observed. Classification accuracy (regardless of the position, spacing between digits or position of the target digit) is 53.7% on average in the 60 Hz case vs. 82.7% for HFR.

ject counting, and digit identification. The approach used herein completes other studies, more concerned with the subjective evaluation of the influence of different displays on comfort, fatigue or pleasantness. It thus provides a complementary approach, relying on objective measures allowing easy quantitative comparisons between different studies. These results match converging evidence from neuroscience, suggesting that neurons in early stages of sensory processing in primary cortical areas, including both vision and other modalities, use the precise time of neural responses to carry information. In the brain, there has been evidence for a high precision, down to the millisecond, of neural coding in different sensory structures [21]–[24]. Although the focus of the present study was on the effects of refresh rate on the perception of moving stimuli, similar experiments could be conducted on different display characteristics (resolution, color, contrast, etc.). Moreover, the present results, although expected, complement the results of psychophysical, electrophysiological, or imaging studies characterizing visual functions that are, more than often, performed with low to medium refresh rate displays (60 to 120 Hz, and more rarely 200 Hz). Taking refresh rate seriously into account should lead either to restricting the range of stimuli and functions that can be studied to what the displaying technologies offer, or to use imaginative workarounds to increase the temporal resolution of the experimental stimulation. A stimulation platform where temporal resolution can be precisely controlled is thus an essential tool in advancing the understanding of how visual motion is processed by the nervous system. Such a platform would further enable experimenters to perform studies requiring a fine temporal resolution or testing biological mechanisms where timing is an important parameter.

Despite the limitations of the platform used in this study (binary display with a single color, specific duty cycle and low spatial resolution), and the choice of medium to high speeds, the present results are of interest for engineers developing screens and projecting devices who seek for increased spatial density, number and resolution of their pixels. This study addresses some of the concerns about the quality of broadcasting and TV images mentioned in the introduction [1], [2], in particular regarding the vast range of temporal dynamics needed to be rendered. In this sense further studies are needed to objectively evaluate how different temporal display characteristics have an impact on human perception, in particular in the case of gray-level or colored displays supporting higher spatial resolutions.

The results of this work are of particular concern for specific class of devices, such as head mounted displays. Head-mounted displays are not only limited to use in virtual environment or augmented reality scenarios. With assistive technologies for visual impaired individuals, the display conveys real-world information, usually captured by a camera, to a retinal implant in order to provide some degrees of visual restoration. In many cases the image itself needs simplification, so as to maximally utilize the limited spatial resolution available [25], [26]. In these cases, increased temporal resolution might compensate for the lack of spatial resolution, for example in the case of sub-retinal implants based on electrodes. Even in recent retinal implants [27] the number of electrodes is limited by the technology used, giving a reduced number of "pixels" for implanted patients.

This forces implanted patients to use alternative scanning techniques, such as moving their heads to explore the environment, since the camera providing input to the implant is often fixed. The different speeds used in this work are compatible with head movement speeds; Pozzo *et al.* [28] and Grossman *et al.* [29], for instance, report a maximum head movement speed of 38 deg/s in various motor tasks.

The increasing use of visual displays in everyday life, and its possible consequences on health, calls for a thorough reevaluation of the effects of frame rate on visual performance, whether it relates to perception and sensitivity or oculomotor behavior.

Acknowledgements

The authors would like to thank J. B. Floderer for his help on the development of the experimental platform.

References

[1] M. G. Armstrong, D. J. Flynn, M. E. Hammond, S. J. E. Jolly, and R. A. Salmon, "High frame-rate television," *SMPTE Motion Imaging J.*, vol. 118, no. 7, pp. 54–59, Oct. 2009.

[2] T. Fujine, Y. Kikuchi, M. Sugino, and Y. Yoshida, "Real-life in-home viewing conditions for flat panel displays and statistical characteristics of broadcast video signal," *Japanese J. Appl. Phys.*, vol. 46, no. 3S, pp. 1358–1362, 2007. [Online]. Available: http://stacks.iop.org/1347-4065/46/i=3S/a=1358

[3] R. Yao *et al.*, *Oculus VR Best Practices Guide*. Menlo Park, CA, USA: Oculus VR, 2014.

[4] Y. Kuroki, T. Nishi, S. Kobayashi, H. Oyaizu, and S. Yoshimura, "A psychophysical study of improvements in motion-image quality by using high frame rates," *J. Soc. Inf. Display*, vol. 15, no. 1, pp. 61–68, Jan. 2007.

[5] Y. Kuroki, "Improvement of {3D} visual image quality by using high frame rate," *J. Soc. Inf. Display*, vol. 20, no. 10, pp. 566–574, 2012. [Online]. Available: http://onlinelibrary.wiley.com/doi/10.1002/jsid.107/abstract

[6] D. M. Hoffman, V. I. Karasev, and M. S. Banks, "Temporal presentation protocols in stereoscopic displays: Flicker visibility, perceived motion, and perceived depth," *J. Soc. Inf. Display*, vol. 19, no. 3, pp. 271–297, 2011. [Online]. Available: http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=3092720&tool=pmcentrez&rendertype=abstract

[7] M. Emoto, Y. Kusakabe, and M. Sugawara, "High-frame-rate motion picture quality and its independence of viewing distance," *J. Display Technol.*, vol. 10, no. 8, pp. 635–641, Aug. 2014.

[8] G. Deffner, "Eye movement recordings to study determinants of image quality in new display technology," *Stud. Vis. Inf. Process.*, vol. 6, pp. 479–490, 1995.

[9] M. Saika *et al.*, "Hyperspectral two-dimensional display with a diffractive grating and a digital mirror device," in *Proc. 9th Int. Conf. Opt.-Photon. Des Fabrication.*, 2014, pp. 13PSp–25.

[10] "Texas instrument DLP Lightcrafter," [Online]. Available: www.ti.com/tool/dlplightcrafter, Accessed on: Mar. 23, 2016.

[11] J. B. Sampsell, "Digital micromirror device and its application to projection displays," *J. Vacuum Sci. Technol. B, Microelectron. Nanometer Struct.*, vol. 12, no. 6, pp. 3242–3246, Nov. 1994.

[12] S. P. McKee, "A local mechanism for differential velocity detection," *Vis. Res.*, vol. 21, no. 4, pp. 491–500, 1981.

[13] S. P. McKee, G. H. Silverman, and K. Nakayama, "Precise velocity discrimination despite random variations in temporal frequency and contrast," *Vis. Res.*, vol. 26, no. 4, pp. 609–619, 1986.

[14] G. A. Orban, J. de Wolf, and H. Maes, "Factors influencing velocity coding in the human visual system," *Vis. Res.*, vol. 24, no. 1, pp. 33–39, 1984.

[15] U. Ilg, Y. Jin, S. Schumann, and U. Schwarz, "Preparation and execution of saccades: The problem of limited capacity of computational resources," *Exp. Brain Res.*, vol. 171, no. 1, pp. 7–15, 2006. [Online]. Available: http://link.springer.com/article/10.1007/s00221-005-0255-z

[16] G. Westheimer, "Eye movement responses to a horizontally moving visual stimulus," *A.M.A. Archives Ophthalmol.*, vol. 52, no. 6, pp. 932–941, Dec. 1954. [Online]. Available: http://dx.doi.org/10.1001/archopht.1954.00920050938013

[17] E. Castet, J. Lorenceau, and C. Bonnet, "The inverse intensity effect is not lost with stimuli in apparent motion," *Vis. Res.*, vol. 33, no. 12, pp. 1697–1708, 1993.

[18] F. W. Campbell and J. Robson, "Application of fourier analysis to the visibility of gratings," *J. Physiol.*, vol. 197, no. 3, pp. 551–566, 1968.

[19] D. Kelly, "Motion and vision. ii. Stabilized spatio-temporal threshold surface," *Josa*, vol. 69, no. 10, pp. 1340–1349, 1979.

[20] A. B. Watson, "High frame rates and human vision: A view through the window of visibility," *SMPTE Motion Imaging J.*, vol. 122, no. 2, pp. 18–32, Mar. 2013.

[21] M. J. Berry, D. K. Warland, and M. Meister, "The structure and precision of retinal spike trains," *Proc. Nat. Acad. Sci. USA*, vol. 94, no. 10, pp. 5411–5416, 1997.

[22] P. Reinagel and R. C. Reid, "Temporal coding of visual information in the thalamus," *J. Neurosci.*, vol. 20, no. 14, pp. 5392–5400, 2000.

[23] G. T. Buracas, A. M. Zador, M. R. DeWeese, and T. D. Albright, "Efficient discrimination of temporal patterns by motion-sensitive neurons in primate visual cortex," *Neuron*, vol. 20, no. 5, pp. 959–969, 1998.

[24] T. J. Blanche, K. Koepsell, N. Swindale, and B. A. Olshausen, "Predicting response variability in the primary visual cortex," *Proc. Comput. Syst. Neuroscience, COSYNE08*, 2008.

[25] W. I. Al-Atabany, M. A. Memon, S. M. Downes, and P. A. Degenaar, "Designing and testing scene enhancement algorithms for patients with retina degenerative disorders," *Biomed. Eng. Online*, vol. 9, p. 27, 2010.

[26] W. Al-Atabany and P. Degenaar, "Scene optimization for optogenetic retinal prosthesis," in *Proc. IEEE Biomed. Circuits Syst. Conf.*, Nov. 2011, pp. 432–435. [Online]. Available: http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=6107820

[27] L. Wang *et al.*, "Photovoltaic retinal prosthesis: Implant fabrication and performance," *J. Neural Eng.*, vol. 9, no. 4, Aug. 2012, Art. no. 046014.

[28] T. Pozzo, A. Berthoz, and L. Lefort, "Head kinematic during various motor tasks in humans," *Progress Brain Res.*, vol. 80, pp. 377–383, 1989.

[29] G. Grossman, R. Leigh, L. Abel, D. Lanska, and S. Thurston, "Frequency and velocity of rotational head perturbations during locomotion," *Exp. Brain Res.*, vol. 70, no. 3, pp. 470–476, 1988.

[30] K. Guttag, "TI DLP diamond pixel," [Online]. Available: http://www.kguttag.com/2012/02/09/ti-dlp-diamond-pixel/, 2012, Accessed on: Mar. 23, 2016].

Sihem Kime received the B.Sc. degree in applied physics in 2009 and the M.Sc. degree in computer science from the Université Pierre et Marie Curie, Paris, France, in 2011. She is currently working toward the Ph.D. degree in computer vision applied to biological vision at the Vision Institute, Paris, France.

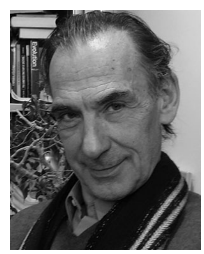
Francesco Galluppi received the B.Sc. degree in electronic engineering from the University of Rome 'Roma Tre', Roma, Italy, in 2005, the M.Sc. degree in cognitive psychology from the University of Rome 'La Sapienza', Roma, Italy, in 2010, and the Ph.D. degree from the University of Manchester, Manchester, U.K., in 2013.

He is a Postdoctoral Research Associate with the Institut de la Vision, University Pierre et Marie Curie, Paris, France. He visited the Departamento de Tecnologa Electrnica of the University of Malaga in 2007, working on robotic assistive technologies. He joined the SpiNNaker Group, University of Manchester, where he worked on neurally inspired hardware systems, sensors, and robots. His interests include studying the biological basis of human behavior, and how technology interacts with it. His current research focus on the use event-based stimulation with assistive technologies for blind people.

Xavier Lagorce received the B.Sc. degree, the Agrégation degree in electrical engineering, and the M.Sc. degree in advanced systems and robotics from the Ecole Normale Supérieure de Cachan, Cachan, France, in 2008, 2010, and 2011, respectively. He is currently working toward the Ph.D. degree in neurally inspired hardware systems and sensors with the Vision Institute, Paris.

Ryad B. Benosman is a Full Professor at the Universite Pierre et Marie Curie, Paris, France.

He leads the Neuromorphic Vision and Natural Computation group. He focuses mainly on neuromorphic engineering, visual computation, and sensing. He is a pioneer of omnidirectional vision systems, complex perception systems, variant scale sensors, and noncentral sensors. His current research interests include the understanding of the computation operated by the visual system with the goal to establish the link between computational and biological vision. He is also invested in applying neuromorphic computation to retina prosthetics and is a cofounder of the startup Pixium Vision.



Jean Lorenceau is the Director of research at the "Centre National de la Recherche Scientifique" and Ecole Normale Supérieurein the "Laboratory of Perceptual Systems." His work bares on visual perception and oculomotor behavior using psychophysics, neuroimaging, and eye-tracking techniques. He developed visual paradigms to study motion perception in healthy humans as well as in patients with neuropathies. He recently discovered a novel approach to eye-based communication, allowing to write uncursive with smooth pursuit eye movements. His current research interests include the development of novel eye-based techniques to identify neuropathies. He is the Head of the "Relais d'Information sur les sciences de la Cognition" (RISC) and the co-founder of the Fondation Cognition.