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Citation: Armengol Urpi, Alexandre and Sanjay E. Sarma. "Sublime: a hands-free virtual reality menu navigation system using a high-frequency SSVEP-based brain-computer interface." Proceedings of the ACM Symposium on Virtual Reality Software and Technology, November 2018, Toyko, Japan, Association for Computing Machinery, November 2018. © 2018 Association for Computing Machinery

As Published: <http://dx.doi.org/10.1145/3281505.3281514>

Publisher: Association for Computing Machinery (ACM)

Persistent URL: <https://hdl.handle.net/1721.1/127842>

Version: Author's final manuscript: final author's manuscript post peer review, without publisher's formatting or copy editing

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Sublime: a Hands-Free Virtual Reality Menu Navigation System Using a High-Frequency SSVEP-based Brain-Computer Interface

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Abstract—In this work we present *Sublime*, a new concept of Steady-State Visually Evoked Potential (SSVEP) based Brain-Computer Interface (BCI) where brain-computer communication occurs by capturing imperceptible visual stimuli integrated in the virtual scene and effortlessly conveying *subliminal* information to a computer. The technology was tested in a Virtual Reality (VR) environment, where the subject could navigate between the different menus by just gazing at them. The ratio between the stimuli frequencies and the refresh rate of the VR display creates an undesired perception of beats for which different solutions are proposed. To inform the user of target activation, real-time feedback in the form of loading bars is incorporated under each selectable object. We conducted experiments with several subjects and though the system is slower than a conventional joystick, users reported a satisfactory overall experience, in part due to the unexpected responsiveness of the system, as well as due to the fact that virtual objects flickered at a rate that did not cause annoyance. Since the imperceptible visual stimuli can be integrated unobtrusively to any element of the virtual world, we conclude that the potential applications of *Sublime* are extensive, especially in situations where knowing user's visual focus can be relevant.

I. INTRODUCTION

Steady-state visually evoked potentials (SSVEP) are brain signals generated at the visual cortex [1], [2], which occur in response to visual stimulation at specific frequencies [3], [4], [5]. When the retina is excited with flickering stimuli at a particular frequency within the 6-90Hz range [1], electrical potentials at the same frequency and its harmonics are generated in the occipital area of the brain. This phenomenon has been widely exploited to build brain-computer interfaces (BCIs) [6]. These BCIs use visual stimuli rendered in computer screens or light sources modulated at a specified frequency to elicit response signals at the visual cortex, which are then captured by EEG equipment and processed to identify which stimulus the subject is looking at. Using SSVEPs, BCIs can be created for a variety of actions including spelling words [7], controlling a robot [8] or playing video games [9]. As for the stimulating frequencies used, it has been widely proved that the brain does not respond uniformly throughout all the spectrum, i.e. it resonates more strongly to some frequencies

than others, giving the highest SSVEP amplitudes in the 6-16Hz band [10], [11]. This is one of the main reasons why most of the SSVEP-based BCI applications use flickering stimuli in the lowest part of the spectrum [6].

SSVEP-based BCIs have also been used within virtual environments (VE) due to their high information transfer rates and negligible user training requirements [12], [13]. Most of these applications superimpose basic geometric shapes—squares or circles—for the flickering stimuli [6], but this sometimes becomes too obtrusive for the virtual scene and makes it less immersive for the user. Hence, making the stimuli part of the scene has also been explored in VE [14] and VR [15]. However, these studies use stimulating frequencies in the low (1-12Hz) or medium (12-25Hz) part of the spectrum, which presents two major disadvantages: first, low frequency flickering lights (5-25Hz) can be annoying and cause visual fatigue to the user [6], and second, flashing stimuli, especially in the 15-25Hz range, have the potential to induce photo-epileptic seizures [16]. In this work we not only overcome these downsides by using the high-frequency band (>40Hz), but we also create a subtle yet powerful concept by establishing a subconscious connection between user and computer thanks to the undetectable visual stimuli.

II. SUBLIME

Sublime is a new concept of SSVEP-based BCI that allows the user to unconsciously communicate *subliminal* information to the computer in a virtual environment. This can happen under two conditions:

- 1) The visual stimuli frequencies must exceed the flicker fusion rate, i.e., the frequency at which a flashing light appears to be steady [17], [18]. SSVEPs can be generated up to 90Hz and the flicker fusion rate is around 40Hz, so there exists a frequency range that allows for the stimulation and consequent generation of SSVEPs even though the user perceives a steady light [19]. As explained above, highest SSVEP amplitudes are given in the 6Hz-16Hz band, so we create these unobtrusive

stimuli at the expense of lower SSVEP power and most likely longer detection times.

- 2) The flickering stimuli takes the form of virtual objects in the scene rather than inserted fiducials such as rectangles or circles. In other words, if the scene contains a chair, the chair itself must flicker. The full screen can be partitioned into several of these stimulating elements, which will be integrated as part of the virtual scene. Then, we use different flickering frequencies to encode object IDs. This can be implemented thanks to the fact that even though multiple stimuli fall within the visual field of the user, only the one that receives the attention focus of the subject will elicit the corresponding SSVEP response [3], [20].

For *Sublime* to come alive, both conditions need to be fulfilled. We tested this in a VR movie-watching environment. The user can navigate between the application menus by looking at the interactive objects and choosing the movie to watch just by gazing at the corresponding cover.

III. MATERIALS AND METHODS

A. Virtual Reality Display Device

For the purposes of this work, a display with a high refresh rate was essential, since we needed to render stimuli above the flicker fusion rate. We used an Oculus Rift VR headset [21], which has a Refresh Rate (RR) of 90Hz and allows us to generate stimulating signals at frequencies up to 45Hz, i.e. half the RR.

B. Visual Stimuli Generation

Stimuli signals generated by the VR display will always be constrained by its Refresh Rate (RR), since rendered images can only be updated once every $\frac{1}{RR}$ seconds, $\frac{1}{90}$ in our case. Therefore, an 'on/off' stimulation pattern (max/min screen luminance respectively) could only generate sub-multiples of the refresh rate. In that case, stimuli signal frequencies would quickly drop below the flicker fusion rate, which is an undesired scenario for the aims of this work. Hence, this study used a sampled sinusoidal stimulation method [22], [23] which allows us to realize stimuli signals at any frequency up to half of the refresh rate. These signals can be generated by modulating the luminance $L(f_{st}, k)$ of the display screen using the following expression:

$$L(f_{st}, k) = 0.5 \sin(2\pi f_{st}(k/RR)) + 0.5 \quad (1)$$

where f_{st} is the flickering frequency of the visual stimulus, k is an integer that indicates the frame index in the sequence and RR corresponds to the refresh rate of the display. $L(f_{st}, k)$ represents a sampled sine of frequency f_{st} with a sampling rate of RR Hz. The dynamic range of the signal is from 0 to 1, where 0 represents dark and 1 maximum luminance.

Since all stimuli frequencies must be higher than the flicker fusion rate and lower than half of the refresh rate, and considering the flicker fusion rate to be 40Hz [17], the targeted frequency band for this work is 40Hz - 45Hz.

C. Beating effect

Sampling a wave of a frequency very close to the Nyquist rate causes the emergence of apparent beats. These beats oscillate at a frequency f_{beat} :

$$f_{beat} = 2(F_s/2 - f_{st}) \quad (2)$$

where F_s is the sampling frequency and f_{st} is the frequency of the sampled signal. Since in this study we have $F_s = 90Hz$, the beats generated oscillate at $f_{beat} = 90 - 2f_{st}$. An example of the apparent beating effect for a 44Hz sine is shown below:

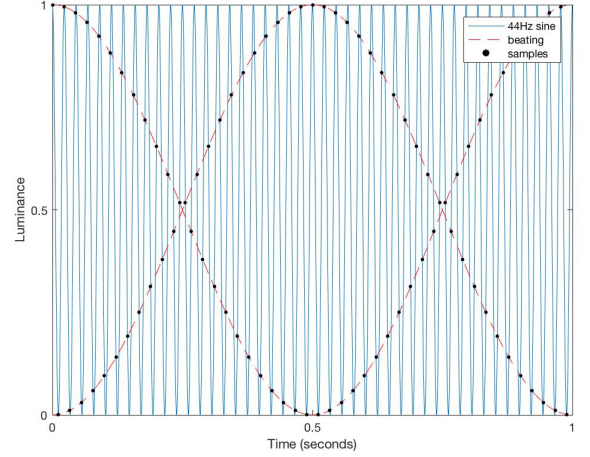


Fig. 1: Blue line shows a 44Hz stimulating sine wave sampled at $RR = 1/90Hz$. The red dashed line shows the beating effect that will be perceived.

This sampling effect translates into an undesired perception of a slowly (f_{beat}) oscillating luminance. In order to minimize the beating effect, a stimulating sine signal with lower amplitude is also utilized:

$$L_2(f_{st}, k) = 0.3 \sin(2\pi f_{st}(k/RR)) + 0.7 \quad (3)$$

In this case, the luminance $L(f_{st}, k)$ is modulated as a sine wave with an amplitude of 0.3, so the signal will range from 0.4 to 1. This will generate smaller amplitude beats, and the fading effect is barely perceived, complying with the purposes of this work of creating perceptually steady stimuli. However, beating effect disappears at the expense of power reduction of the stimulus and consequently of the SSVEPs. This may cause the SSVEPs to be buried in noise and lead to the need for longer SSVEP measurement times, as can be seen in section X. As a consequence, a compromise needs to be found between the signal power and the perceivable beating effect.

Without reducing the signal amplitude, the beating effect will be perceivable as long as $f_{beat} \leq f_{fusion}$. Solving for the refresh rate of the display and assuming $f_{fusion} = 40Hz$ it leads to $RR \leq 2f_{st} + 40Hz$. Therefore, the minimum refresh rate that will allow for maximized amplitudes of the visual stimuli while preserving their non-perceptiveness is given by

$$RR_{min} \geq 2f_{st} + 40Hz \quad (4)$$

The VR headset available for this study has a refresh rate of 90Hz, which does not fulfill Equation 4 for stimulating frequencies f_{st} higher than f_{fusion} . Thus, amplitude reduction of the stimuli signal will be required to prevent the user from noticing the beating effect. This will affect SSVEP amplitudes and argues for higher refresh rate displays in the future.

IV. VIRTUAL REALITY APPLICATION

A. Main Menu

The virtual environment we present to prove the concept of our system was developed in Unity3D [24] and consists of two different type of scenes. The starting one is a main menu with four different movie covers that the user can select. Each movie cover has a different stimulating signal associated, with frequencies $f_{st} = \{42, 43, 44, 45\}Hz$. The user can pick the movie to watch by just gazing at the desired cover without the need of any joystick or hand controller. The corresponding SSVEP signals generated will be detected by the EEG electrodes and the application will transition to the selected movie playback scene.

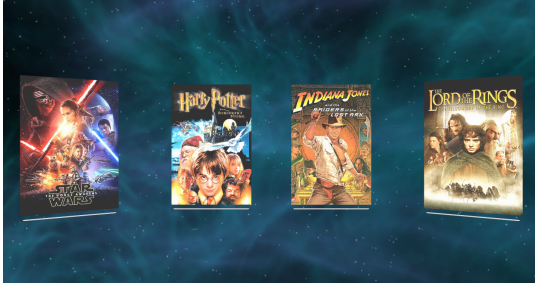


Fig. 2: Screenshot of the movie covers the user sees in the main menu.

B. Movie Playback Menu

This scene plays the movie the user selected in the main menu. In the bottom-left corner there is a selectable object to allow the user navigate back to the main menu. It is also an integrated visual stimulus with its associated frequency $f_{st} = 42Hz$ and the user may look at it to stop the movie and switch to the starting menu.

C. Real-time Feedback

In order to inform the users that the system is responsive to their intentions, we included real-time feedback in the form of loading bars below each selectable object. When the system detects the user is gazing at an object, the corresponding bar starts loading, and it takes 4 seconds to fully charge and begin the transition to the selected scene. In the case the user stops gazing at the loading object, the bar automatically resets and the scene transition is suspended.



Fig. 3: Star Wars Episode VIII playing in the movie menu.



Fig. 4: Loading bars for two different selectable objects. Figure 4b shows the flickering object that allows the user to return to the main menu.

V. EEG RECORDING EQUIPMENT

Aligning with the interests of this work to build a non-invasive system and to keep the user unaware of the brain-computer communication taking place, we wanted to avoid the bulkiness of an EEG electrode cap. Instead, we directly attached EEG electrodes to the VR headset. Oculus Rift has a triangle-shaped back strap that cradles the back of the head and is equipped with part of the headset tracking system. This shape allowed us to locate three EEG electrodes in positions Pz, O1 and O2 according to the international 10-20 system [25]. Reference and ground electrodes were placed in the ear lobes with earclips. As for the EEG recording equipment, we used OpenBCI Ganglion board which allows for bluetooth low energy data transmission and has a sampling rate of $200Hz$ [26].

VI. SSVEP DETECTION

A. Canonical Correlation Analysis

In order to pick up the elicited brain signals, we utilized canonical correlation analysis (CCA), a widely used method for SSVEP detection [27], [28], [29]. Given two variable sets X, Y and their linear combinations $x = XW_x^T$, $y = YW_y^T$, CCA finds the weight vectors W_x and W_y which maximize the correlation ρ between x and y by solving the following:

$$\max_{W_x, W_y} \rho = \frac{E[W_x X^T Y W_y^T]}{\sqrt{E[W_x X^T X W_x^T] E[W_y Y^T Y W_y^T]}} \quad (5)$$

In our approach we define $X \in \mathbb{R}^{L \times N}$ as the recorded EEG data, where L and N denote the number of samples of the EEG signal and the number of EEG channels respectively. Since we use three electrodes ($N = 3$) the matrix X takes the form:

$$X = [X_1 \ X_2 \ X_3] \quad (6)$$

where $X_i \in \mathbb{R}^{L \times 1}$. On the other hand, we define $Y_f \in \mathbb{R}^{L \times 2H}$ as the artificially generated sinusoidal signals of frequency f and its multiples used as the reference, where H represents the number of harmonics. Note that the duration of the signals X and Y_f must be the same. Each submatrix of Y_f contains the pair $\cos(2\pi hft)$ and $\sin(2\pi hft)$, where $h = 1, 2, \dots, H$. Several studies have shown that the amplitude of the SSVEP (fundamental $h = 1$ and harmonics $h > 1$) resulting from high stimulation frequencies ($> 40\text{Hz}$) is considerably lower than in low-frequency SSVEP [1], [11]. Therefore, in our approach we only considered the fundamental frequency $H = 1$ for the reference signals Y_f , giving:

$$Y_f = [\cos(2\pi ft) \ \sin(2\pi ft)] \quad (7)$$

Applying CCA to X and Y_f , the correlation will be maximized by enhancing the part of the evoked response (present in Y_f), and by reducing the noise (not present in Y_f), thereby improving the signal-to-noise ratio of the filtered signal x .

Since we have four possible stimulation frequencies ($f_{st} = \{42, 43, 44, 45\}\text{Hz}$), we define four different reference signal matrices Y_f : $Y_{42}, Y_{43}, Y_{44}, Y_{45}$. Then, we obtain a correlation value ρ_f for each pair Y_f, X and identify the targeted frequency as the one that gives a higher ρ_f . For every data segment, we can define a correlation vector $R \in \mathbb{R}_{\geq 0}^{1 \times 4}$:

$$R = [\rho_{42} \ \rho_{43} \ \rho_{44} \ \rho_{45}] \quad (8)$$

which contains the four correlation values resulting from applying CCA four times.

B. Logistic Regression

In order to discriminate whether an elicited SSVEP is present in the recorded EEG signals we need to define the condition the maximum $\rho_{f_{max}}$ needs to fulfill with respect to the other three ρ_f . Since it is not simple to find this condition empirically, we used logistic regression as a simple binary classification model, which takes as input the following features derived from the correlation vector R :

- Standard deviation of correlations:

$$S = \sqrt{\frac{\sum_{f=1}^4 (\rho_f - \mu_R)^2}{3}} \quad (9)$$

- Difference between maximum correlation $\rho_{f_{max}}$ and the second highest one.
- Difference between maximum correlation $\rho_{f_{max}}$ and sum of the other three.

Taking these three features as input, the binary model outputs a positive or negative answer. If positive, our system

considers the recorded EEG signal contains elicited SSVEP and the targeted frequency will be the one corresponding to the maximum correlation $\rho_{f_{max}}$. In the case of a negative response, our approach assumes the EEG is empty of SSVEP and that the user is not looking at any stimulus.

VII. REAL-TIME DATA PROCESSING

EEG signals recorded are processed in 5 seconds time windows, with 4 seconds of overlap so that the system updates every second. Each 5-second worth of raw EEG is first band-pass filtered with a finite impulse response filter of order 10 and cutoff frequencies 10Hz and 50Hz. Then, CCA is applied to the filtered data segment and each reference signal matrix Y_f , with which the vector of correlations R is obtained. Finally, the trained logistic regression classification model is applied to the features computed from R and a system output is given.

In this approach we prioritize minimizing false positives since they can be annoying for users in such an application where the human-computer communication happens in the "background". Thus, the state of the VR application will not be changed until two equal consecutive outputs are given by the SSVEP detection algorithm. This applies to both starting or suspending the loading process of a gazed object.

VIII. SYSTEM CONFIGURATION

The different system blocks are connected as follows:

- The Oculus Rift VR headset is connected to a computer running the Unity3D application.
- EEG data recorded by OpenBCI's Ganglion board is transmitted through Bluetooth Low Energy (BLE) to a computer running Matlab [30].
- Matlab code takes care of the real-time EEG signal processing and SSVEP detection.
- Matlab is connected to the Unity3D application via TCP/IP and sends updated information when applicable.

Figure 5 shows a scheme of the explained system configuration.

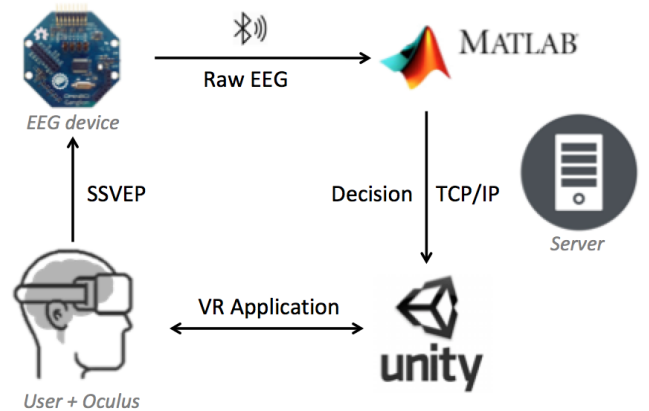


Fig. 5: System blocks configuration.

IX. EXPERIMENTS

A. Subjects

3 participants aged between 20 and 30 years old volunteered for the experiment. Even though stimuli frequencies were much higher than those associated with seizures, we made sure that participants had not had episodes in the past. All participants signed an informed consent form and the whole experimental procedure was approved by the MIT Committee on the Use of Humans as Experimental Subjects (COUHES). The subjects were seated on an armchair behind an office table and wore the VR headset during the whole experiment.

B. Experiment 1: Navigation Time

To assess the different aspects that characterize this work, the experiments were divided into two types. The first one consisted on measuring the time it took for each user to complete a predefined navigation task so that the Information Transfer Rate (ITR) could be computed. The second one allowed for a subjective evaluation of the technology where the user could freely navigate within the application and report his or her experience.

In the first experiment, the user had to navigate to each of the four movie playback menus, returning to the main menu in between. In order to evaluate the effect of reducing the amplitudes of the stimuli to eliminate the beating perception, each user completed this task twice, first using stimuli with maximum amplitudes $L()$ and second using reduced amplitude stimuli $L_2()$ – see Equation 1 and Equation 3 respectively.

C. Experiment 2: Subjective Experience

This experiment consisted on letting the subjects interact freely with the application and answer a survey in the end, which is a common way of measuring a subjective system performance [31]. Again, this task was completed twice, one time with each type of stimulation signals. The questions asked in the survey were the following:

- 1) "How easy was it to navigate between menus?"
- 2) "How would you quantify the perception of flickering, if any?"
- 3) "How would you rate the overall experience of using this system?"

All ratings had to be evaluated in a scale from 0 to 5.

X. RESULTS

Results for Experiments 1 and 2 can be found in Tables I and II respectively. Navigation time corresponds to the time the subjects spent completing the task for Experiment 1. The Information Transfer Rate (ITR) was measured in bits per minute [32]. Each navigation task consisted of detecting the correct stimulus 8 times (4 movies and 4 menu returns), so $ITR = 8 \times 60/T \times \log_2 4$, where T corresponds to the navigation time minus the loading time of all target objects, that is $4s \times 8 = 32$ seconds.

There were no misclassifications during the experiments, so accuracy of the system was 100%. This high accuracy is in

part due to the fact that we aimed to minimize false positives, at the expense of response time and ITR. As explained above, this was accomplished by requiring two equal classifications in a row to start loading an object.

TABLE I

Stimulation signal		S1	S2	S3	Average
$L()$	Navigation time (sec)	57	63	64	61.3
	ITR (bits/min)	16.8	15.2	15	15.7
$L_2()$	Navigation time (sec)	64	75	73	70.7
	ITR (bits/min)	15	12.8	13.1	13.6

TABLE II

Stimulation signal		S1	S2	S3	Average
$L()$	1) How easy to use?	5	4	4	4.3
	2) Perception of flickering?	5	5	5	5
	3) Overall experience?	3	3	4	3.3
$L_2()$	1) How easy to use?	4	2	3	3
	2) Perception of flickering?	1	1	1	1
	3) Overall experience?	4	3	5	4

As expected, we can see that navigation times using full amplitude stimuli ($L()$) are shorter than using L_2 , and therefore ITR is higher. This is tightly related to the fact that, on average, users found easier to use the first approach, which gives faster responses.

Regarding the question in perception of flickering, highest values are given to the approach with $L()$ due to the beating effect. The fact that lowest values of flickering perception are given to L_2 stimuli proves that our proposed solution to minimize the beating effect is valid.

Finally, the ratings for the overall experience question are higher for L_2 , that is, for the non-beating stimuli approach. This shows that even though subjects found it easier to use the first approach, they still prefer the experience of unobtrusive BCI with imperceptible flickering stimuli.

XI. DISCUSSION

Results show that the system was tested with success, giving 100% of accuracy and good overall experience for the non-beating stimulating signals. ITRs obtained are in general lower than the average ITRs in SSVEP-based BCIs found in literature [6]. This is due to the fact of using high-frequency stimuli (as opposed to the vast majority of other works using low-frequency stimuli) as well as because we prioritize accuracy rather than time response, for which we wait for two equal classifications in a row to activate a target and use long (5-second) detection windows. Despite this, the fact that subjects preferred the experience when using the application with non-perceivable signals even though the application latency is greater importantly endorses the potential of *Sublime*.

The amplitude reduction of stimulating signals to generate non-perceivable flickering objects reduces the power of the elicited SSVEP and therefore increases detection time as shown. A higher refresh rate (see Equation 4) would allow for full amplitude stimulating signals and increasing ITR. There

already exist 120Hz VR displays, but it is believed that much higher refresh rates will be needed in the future to achieve a fully comfortable Virtual Reality experience. That is where *Sublime* will have most applicability.

The fact that stimuli can be integrated to any part of the virtual scene and are relatively imperceptible for the user enables *Sublime* to be used not only as a navigation tool, but also as a way to interact with the virtual world, to change the gaming experience, or to simply detect where the user's attention is. As opposed to other BCIs, SSVEP-based BCIs require negligible training time for the user, which also contributes to increase the applicability of this system.

We have also placed emphasis on the importance for *Sublime* to be unobtrusive in the virtual scene, but the loading bars added in this demo may be undesired in some other scenarios. Therefore, instead of using loading bars, we believe that user feedback could be provided by changing the color or the shape of the virtual elements, for instance.

In this work we have assumed that flicker fusion rate is at 40Hz but there is extensive literature proving that this rate may be influenced by stimuli color, luminance, background, shape, subject's age and even retinal eccentricity among others [33], [34], [35], [36]. Therefore, we believe flicker fusion rate should be addressed and further characterized in future work for eventual applications of this technology.

XII. CONCLUSION

We have presented *Sublime*, an SSVEP-based brain-computer interface where the user unconsciously conveys *subliminal* information to a computer thanks to using high-frequency (and therefore non-perceivable) stimulation signals integrated in the virtual scene. The system has been successfully tested as a menu navigation tool in a Virtual Reality environment. The fixed 90Hz refresh rate of the VR display causes undesired beats that were perceived by the user when maximum amplitude signals were used, so we proposed to utilize signals with reduced amplitude to minimize this effect. Experiments with five subjects have shown that although time response is larger with the non-beating stimulating signals, all users reported a better overall experience when using these. We conclude that this is not only due to the fact that these signals don't cause visual fatigue nor are annoying after a while, but also because of the positive user experience when the system responds to user's gaze at what only seem steady virtual objects. The future of VR displays seems to be pointing towards higher refresh rates which would allow to use non-beating stimuli signals with maximum amplitudes and therefore reduce the system time response. Since *Sublime* is unobtrusive for the virtual scenes—i.e. virtual scenes with or without active stimuli have the same appearance for the user—we believe that potential applications of this technology are very extensive, not only to be used as a navigation tool but for any other application where knowing where the user's visual focus is can be of value.

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