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Implementation of a compact optical architecture for visual psychophysical tests based on spatial light modulators

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Summary. — Spatial light modulators (SLM) are increasingly used as active optical elements for wavefront manipulation in holography, adaptive optics, and beam shaping. In this work, we present the implementation and test of a compact optical system based on a computer-controlled SLM to perform psychophysical tests on visual acuity and contrast sensitivity. The Fourier transform of the desired pattern, *e.g.*, Snellen optotype or Gabor grating, is encoded and uploaded on the SLM and customized in terms of final size, contrast, orientation, and position. The device is controlled with specific software in order to conduct psychophysical tests and converge quickly towards a threshold estimate. Thanks to its versatility and scalability, the platform can be extended straightforwardly to any visual test, and a preliminary study on the effect of stochastic resonance on contrast sensitivity threshold is here shown and discussed.

1. – Introduction

Psychophysical tests represent the essence of the optometrist's activity, providing a well-defined procedure to correlate an objective physical stimulus with its subjective perception and obtain an estimate of the perceptual threshold [1, 2]. For instance, the well-known Monoyer progression is usually proposed according to the method of descending limits to estimate visual acuity and it starts presenting a stimulus (a letter) well above the threshold and then decreasing the stimulus intensity (letter size) in small steps until the subject cannot detect, resolve, or recognize it. The progression has been printed and posted on the wall for decades. Then, the advent and spread of electronic displays and devices has extended the variety and possibilities of psychophysical tests and versatile programs, such as FrACT [3], are available to perform visual acuity (VA) and contrast sensitivity (CS) tests, and more.

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The aim of this study is to investigate a novel projective method to generate target images using a spatial light modulator (SLM). Spatial light modulators are dynamic optical tools used in various fields of optics and photonics to control and structure a laser beam, generating complex patterns and images on demand [4].

The technology is based on the optical and electrical anisotropy of nematic liquid crystal (LC) molecules placed between two electrodes. By controlling the voltange, the orientation of the molecules changes, inducing a variable phase shift on the light that passes through the medium. Using complex electronics, it is possible to control the voltage pixel by pixel on a matrix of LC cells, and therefore the phase shift imparted to a beam that illuminates the display of the instrument. Using this device, it is possible to implement any optical element in a diffractive form and shape the wavefront of a standard laser in order to form a specific image at a certain distance.

We describe here the design and test of a portable and versatile platform based on SLM to measure visual acuity (VA) and contrast sensitivity (CS). In order to show the potentiality of the platform, we decided to upgrade the instrument for the analysis of the particular phenomenon of stochastic resonance. In the theory of nonlinear dynamic systems, stochastic resonance is a mechanism by which a nonlinear system (such as the brain), in the presence of noise, becomes sensitive to external perturbations that are too weak to affect it in the absence of such noise [5]. In vision science, this phenomenon manifests itself in the perception of subthreshold signals by adding an optimal amount of noise [6-8].

2. – Experimental setup design and test

In the paraxial regime, the propagation of a wavefield U_z at a distance z from a phase shaping element (see fig. 1) is given by the Fresnel-Kirchhoff diffraction integral [9]

$$U_z(u,v) = \frac{e^{ikz}}{i\lambda z} \int\int U^{(i)}(x,y) e^{i\Omega(x,y)} e^{-ik\frac{xu+yv}{z}} \mathrm{d}x\mathrm{d}y, \tag{1}$$

where $U^{(i)}$ is the input field, Ω is the phase function of the optical element, (x, y) are Cartesian coordinates on the input plane, $k = 2\pi/\lambda$ is the wave-vector modulus, being λ the wavelength. The integral expresses a 2D Fourier transform (FT) on the spatial coordinates, that is

$$U_z \propto FT\left\{U^{(i)}(x,y)e^{i\Omega(x,y)}\right\}\left(\frac{u}{\lambda z}, \frac{v}{\lambda z}\right). \tag{2}$$

Therefore, if we want to shape the input laser into a desired image at a given distance, we have to encode its Fourier transform on the SLM display. Due to experimental constraints, *e.g.*, phase-only modulation of the SLM, an iterative Fourier Transform algorithm (IFTA) [10] is implemented to converge to an optimal phase-only pattern for the Fourier transform of the image.

The experimental setup has been assembled on a portable optical breadboard. A diode laser (CPS180, 1 mW, Thorlabs) at 635 nm is linearly polarized (LPVISE100-A, Thorlabs) and illuminates a computer-controlled liquid crystals on Silicon (LCoS) SLM (PLUTO-2.1-VIS-014, Holoeye, pixel size 8 μm, resolution 1920 $\times$ 1080, bit-depth 8 bit) (fig. 2). A 50:50 beam-splitter is used to separate the input and the reflected beams and redirect the structured output towards a screan placed at a distance of around 30 cm,

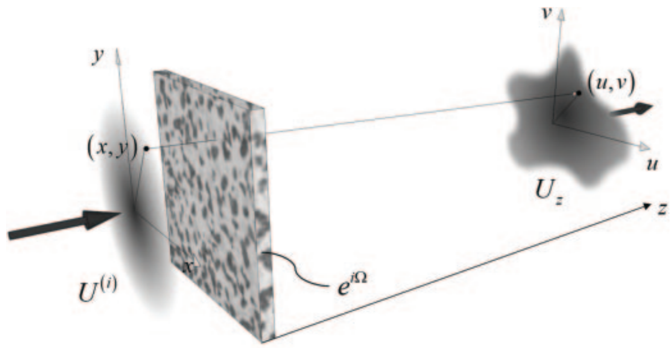

Fig. 1. – Scheme of wavefront propagation after illuminating a phase-only optical element with phase map Ω.

where the target images are projected. For each target, the Fourier transform is computed using an iterative Fourier transform algorithm (Gerchberg-Saxton method) [11]. The Fourier transform of the target is saved as a greyscale 8-bit bitmap file and uploaded on the SLM using custom routines developed in MatLab environment.

During the psychophysical tests, different targets are presented in sequence according to a 1-up 2-down staircase [12]. In particular, Snellen optotypes (C-D-E-F-L-O-P-T-Z) with different size are used for visual acuity tests (distance of 3 m from the chinrest, 30 trials in total), while for contrast sensitivity we chose Gabor gratings [13] with different contrast values and orientations (0°, 45°, 90°, or 135°) (distance 1 m, 25 trials). As shown in fig. 3, the size of the letter is decreased after two correct answers in sequence, while it is sufficient a single wrong answer to increase the letter size. The same procedure is performed with Gabor gratings, changing the constrast accordingly after questioning the grating orientation in order to check the correct identification by the subject. After a proper number of iterations, the estimate of the threshold is obtained from the average of the reversal points, including the last one.

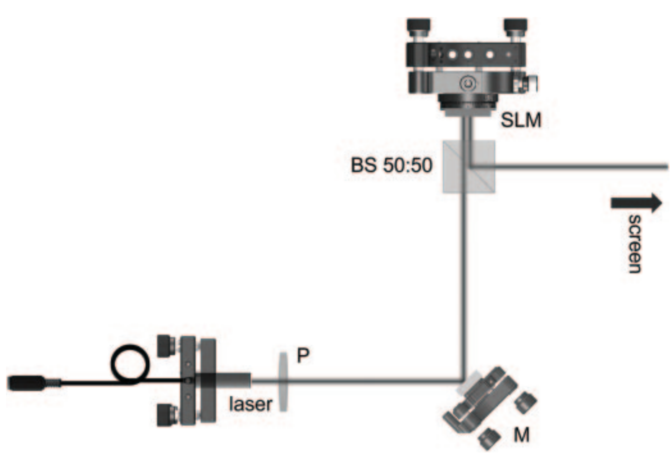

Fig. 2. – Scheme of the experimental setup. The output of a diode laser at 635 nm is linearly polarized (P) and illuminates a computer-controlled spatial light modulator (SLM) for the generation of the desired target on a screen. M: mirrors. BS: 50:50 beam-splitter.

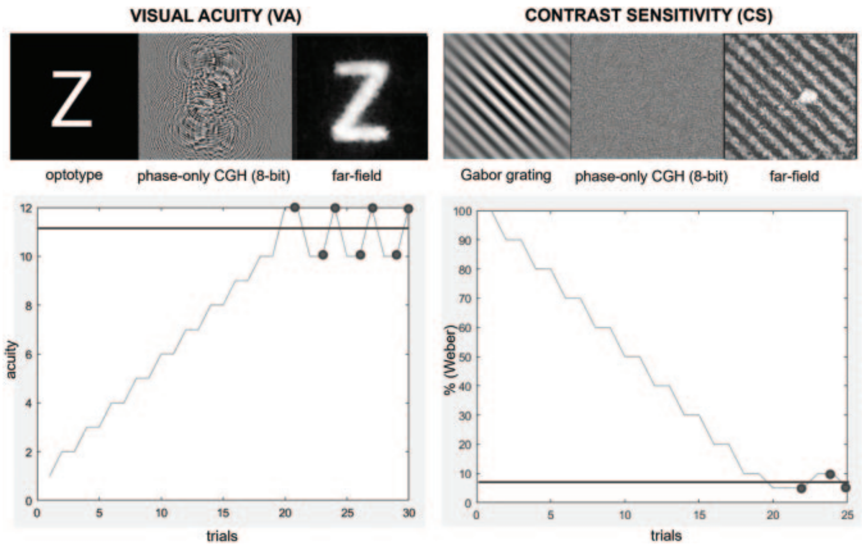

Fig. 3. – Example of 1-up 2-down staircases during tests for visual acuity (on the left) and contrast sensitivity (on the right). The intensity of the stimulus (letter size or grating constrast) is decreased after two right answers in sequence, otherwise it is increased. The threshold is calculated as the average of the reversal points including the last value. On the top: original target, 8-bit greyscale Fourier transform, and picture of the image on the screen.

3. – Investigation of stochastic resonance

3˙1. *Setup upgrade.* – The setup has been upgraded for stochastic resonance analysis by adding a second optical arm for the controlled generation of noise. As shown in fig. 4, a second laser (CPS180, Thorlabs) is polarized and illuminates a rotating half-wave plate (HWP, WPH10M-633, Thorlabs) for polarization rotation. A second polarizer in cascade, aligned to the first one, filters the polarization component on the plane. The two beams illuminates the two distinct halves of the SLM display for independent wave-front modulation. While the first beam is exploited for target generation as described above, the second one is used for the generation of a noise pattern which overlaps with the target on the screen. In particular, the pattern of the illuminated half of the SLM is computed to generate a Gaussian intensity distribution $\propto \exp[-(l-\mu)^2/(2\sigma^2)]$, where l is the grey level between 0 and 255, and $\mu = 127$. Acting on the HWP orientation, it is possible to control the intensity of the second beam and therefore the total amount of the carried noise contribution, while the noise dispersion σ is defined during the generation of the noise pattern using the MatLab script.

3˙2. *Preliminary tests and results.* – In order to investigate the effect of noise on the perceptual threshold, we focused the analysis on contrast sensitivity. The tests were performed on a group of 12 people (7 W, 5 M) of different age (27.6 ± 5.4). Tests were binocular and performed wearing the usual correction. At first, an estimate of the CS threshold was obtained performing 3 times the 1-up 2-down staircase. Then, a sequence of 15 trials below the threshold was presented, with the same constrast level but different orientations, and after each sequence the accuracy was calculated as the fraction of correct answers. The test has been repeated for 10 different intensities of the noise, *i.e.*, 10 different rotations of the HWP from 0° to 90°, step 10°, and 6 different

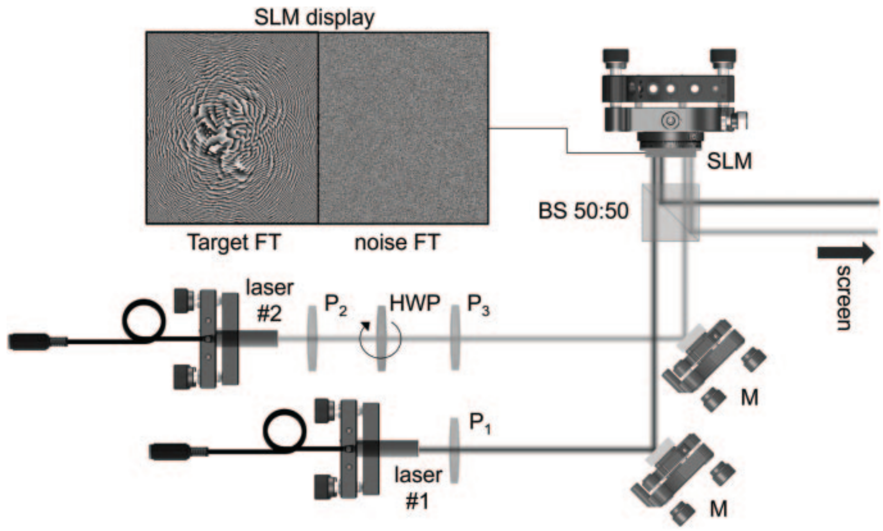

Fig. 4. – Experimental scheme for stochastic resonance investigation. With respect to the setup in fig. 2, a second laser is added. The laser is polarized (P_2) and the cascade of a half-wave plate (HWP) and a second polarizer (P_3) is used to tune its intensity. The two lasers illuminate the two halves of the SLM for the independent control of target and noise on a screen.

values of the noise dispersion σ (5, 10, 20–80 step 20). ANOVA analysis pointed out an effect of noise intensity on the perceptual threshold. As shown in fig. 5, the preliminary results show an effect of noise on subject accuracy. There appears to be an improvement, even though weak, with the addition of noise, and then a progressive worsening as the intensity of the noise increases (p-value < 0.05).

4. – Conclusions

To conclude, we presented here the preliminary tests of a novel setup, never shown in the literature to the best of our knowledge, based on spatial light modulators and specifically designed and programmed to perform optometric and psychophysical tests. In particular, the setup has been prepared to measure visual acuity and contrast sensitivity. It may provide the first prototype of a potential series of portable, compact, and versatile optometric devices for the realization of a rich variety of programmable tests.

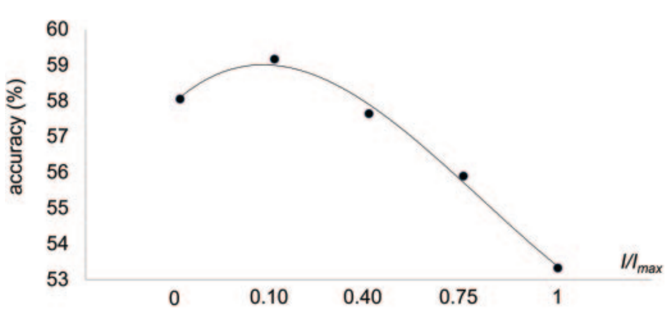

Fig. 5. – Accuracy as a function of the noise intensity.

All the optical elements and sources can be integrated and miniaturized into a compact architecture, reducing the cost and footprint of high-resolution displays currently used for visual tests. The possibility to substitute the lasers with different wavelengths or broadband sources open to investigations on the potential role of colour on perception and on the effect of noise. With respect to previous studies in the field, noise can be added to the stimulus as an external contribution and controlled independently, without the need of updating the target itself. A preliminary analysis on stochastic resonance has been performed. However, while the results prove that noise tangibly and measurably affects visual perception, further investigation on a larger scale is needed to validate the data in relation to stochastic resonance.

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