Solid-State Synapses Modulated by Wavelength-Sensitive Temporal Correlations in Optic Sensory Inputs

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ABSTRACT: Recently, inspired by neurobiological information processing, correlation-based learning has been expressed physically in nonbiological systems by exploiting time causality of electric signals. Yet, the capability to learn from visual events requires extending these concepts to optical stimuli. Here we show a solid-state system that is sensitive

to 100-millisecond-scale timing of pairs of light stimuli with complementary short/long visible wavelengths, causing asymmetric changes of photoconductance. This property endows optical signals with time causality, leading to wavelength-sensitive time correlations with timescales comparable with those of perceptual recognition. Based on these observations, we propose that complex information can be extracted from visual patterns imprinted as spatiotemporal modulations of persistent photoconductance. We suggest that this capability may stimulate neuromorphic hybrid electronic/photonic systems to construct biomimetic spatial memory and navigation maps inspired from neurobiology.

KEYWORDS: neuromorphic engineering, photoconductance, two-dimensional systems, oxide interfaces, spike-timing-dependent plasticity

INTRODUCTION

In nervous systems, sensory neurons convert stimuli into action potentials that send information to the brain. Inspired by these neurobiological processes, neuromorphic engineering has emulated cognitive functionality in several nonbiological systems, including memristors,^{1, 2} phase-change materials,³ spin oscillators^{4, 5} or ferroelectric junctions.⁶ Similarly, biological transduction has inspired technological developments, e.g., the emergence of neuromorphic vision chips,^{7,8} which enable real-time analysis of high-speed movements unattainable by conventional technologies.^{9,10} Underlying brain cognitive capabilities is the concept of synaptic plasticity,¹¹ whereby the strength of excitatory (inhibitory) synapses can increase (decrease) over time in response to changes in neuron activity. A particularly relevant case occurs when synaptic modulation is driven by the correlated activity of pre- and postsynaptic neurons, which was initially postulated to stabilize neuronal activity patterns in the brain that imply learning.¹² Inspired by such principles, time-correlated synaptic changes in the form of spike-time-dependent-plasticity (STDP) was first suggested in computational neuroscience¹¹ and experimental evidence accumulated in biological systems.¹³⁻¹⁵ Along these lines, solid-state synapses based on memristors have been demonstrated to exploit causality of electric signals and enabling unsupervised learning.⁶ Yet, the development of artificial neural networks interacting with a variety of environmental inputs requires the extension of time-correlations beyond electric signals. Particularly, correlated timing of optical stimuli would enable a whole new perspective on biomimetic artificial vision, where learning rules could be applied to complex visual events.¹⁶

In this work we show that causally correlated potentiation and depression of synaptic plasticity can be replicated in a solid-state system that exhibits persistent photoconductance (PPC),^{17,18} where the conductance suddenly changes after illumination with visible, ultraviolet light or X-rays¹⁹ and the effect persists over long periods after the light is off. This phenomenon,

observed in many semiconductors, is generally caused by DX centers,²⁰ whereby shallow donors undergo a large lattice relaxation, thus preventing the return of the carrier back to the initial state after photoexcitation¹⁷ (**Figure 1a**). Our study reveals that the conductance of the PPC system can be increased or decreased in a controlled way by external optical stimuli formed by combinations of short-/ long-wavelength pairs of visible light pulses, where the control is done at 100 millisecond-scales, comparable with timescales for perceptual recognition. The synaptic modulation can be fine-tuned by the order of the time arrivals of the light pulses as well as by their duration and, most remarkably, it is wavelength-sensitive, namely, the particular selection of the wavelengths of the light pulses is critical to the synaptic modulation. We posit that wavelength-sensitive time-correlations in optical stimuli can be exploited to use information encoded in light to build spatial memory and navigation maps akin to processes occurring in brains, with timescales comparable with cognitive processes.

RESULTS

The system under study is the interface between SrTiO₃ (STO) and LaAlO₃ (LAO), two wide-bandgap semiconductors. Despite the insulating character of the constituent materials, a highly-conductive two-dimensional electron system (2DES) develops across an nm-thick region around the interface.²¹ This 2DES hosts a number of properties including superconductivity,²² large spin-orbit fields²³ and, importantly for the context of this work, PPC.²⁴ Our study comprises epitaxial LAO thin films with thickness $t \approx 1.1 - 5.3$ nm (3 – 14 unit cells, u.c.) grown on (001)-oriented STO crystals (see Methods for details on materials preparation and Figure S1 for structural characterization). By way of illustration, Figure 1b summarizes the main features of PPC by displaying data extracted from measurements done with wide pulses (tens of seconds in contrast to millisecond-range pulses studied below) at four wavelengths in the visible –red ($\lambda = 638$ nm), green ($\lambda = 520$ nm), blue ($\lambda = 450$ nm) and

violet ($\lambda = 405$ nm)– and different irradiance values. In these experiments, Hall-bar devices were defined by optical lithography (Figure 1c). The transport was characterized by injecting currents (typically $I \approx 1$ μ A) along two contacts, and measuring the longitudinal resistance by probing the voltage on two other contacts (typical resistance values were $R \approx 100 - 500$ k Ω , see also Supplementary Note S9 and Figure S13 for more details on the voltage readout). Photoexcitation experiments were carried out at room temperature using high-numerical-aperture (high-NA) focusing (Figure 1d). After switching the light on, there is a sudden increase of conductance (Figure 1b) that we quantify as $\frac{\delta\sigma_{ph}(t)}{\sigma_0} = \frac{\sigma_{ph}(t) - \sigma_0}{\sigma_0}$, where σ_0 is the conductance prior to switching the light on and $\sigma_{ph}(t)$ is the time-dependent conductance. The analysis of the time-dependent response shows that light stimuli can be detected down to the range of 50 – 100 μ s for visible wavelengths (**Figure 2a,b**). Furthermore, measurements of $\delta\sigma_{ph}(t)/\sigma_0$ after illumination with light pulses of varying durations and different illumination conditions demonstrate a plastic PPC response that can be fine-tuned by controlling the cumulated illumination time (Figure 2c and 2d). This is also shown in Figures 2e,f , which display data selected from incoming light pulses of cumulated times ranging between 5 and 250 milliseconds. As Figure 2f shows, in spite of some occasional irregularity (see, e.g., right panel of Figure 2f corresponding to data indicated by the arrow in Figure 2d), the photoconductance response can be fine-tuned by the cumulated time, as can be seen in Figure 2e. We also note that the photoconductive response shows an uneven dependence on wavelength, with an apparent unexpected smaller responsiveness to green light (figure 2c). We suggest that the particulars of the spectral response are related to the details of the density of states linked to the energy landscape of the involved defects, as well as to the features of the conduction band. Below we elaborate further on these aspects in connection with the plausible microscopic mechanisms at work for the observed PPC response.

Motivated by computational approaches to use visual patterns for learning –similar to time correlations observed in biological systems^{16,25}– we explored the possibility to express physically such concepts using persistent photoconductance. The basic idea is to combine light pulses (sensory inputs) of two complementary wavelengths that have opposite effects on the plasticity of PPC. With this in mind, we tried different combinations of wavelengths in the visible. First, we consider the illumination with short pulses of red, green or blue followed by violet. In this case, in agreement with the cumulative effect discussed in the previous discussion, illumination with the second pulse just increases the photoconductance above the value set by the first pulse (see the left upper panel of **Figure 3a** for red followed by violet). However, the outcome is different when we *reverse* the timing: if violet pulses are followed by green or red, the photoconductance is *decreased* with respect to the first pulse (right upper panel of Figure 3a and Figure S5 and S6, Supporting Information). This unexpected outcome depends on the wavelength used for the second pulse: the suppression of photoconductance is the largest for red and diminishes progressively towards blue (Figure S5, Supporting Information). This observation hints at the use of time correlations between long and short wavelengths to drive synaptic changes. Indeed, as shown in the Supplementary Note S10 and Figure S14, multiple-pulse sequences of long-/short- wavelength timed pulses can be used to modulate the conductance enabling spike-timing-dependent plasticity. This is an important observation, as it demonstrates that STDP protocols can be also used with optical stimulation, provided that wavelength-sensitive time correlations are exploited.

To illustrate how these correlations can be used, we select red and violet wavelengths to establish a formal equivalence with pre- and post-synaptic neurons,¹¹ respectively (see the sketches in Figure 3a). The first pulse, red or violet, sets the initial photoconductance $\Sigma^0 \equiv [\delta\sigma_{ph}(\Delta t^0)/\sigma_0]$. Subsequently, depending on the relative timing of the short-/long-wavelength in the two-pulse sequence, the second pulse either increases ($\Sigma^{(+)} \equiv \Sigma^0 + |\Delta\Sigma^{(+)}|$),

Figure 3a left upper panel) or decreases the conductance ($\Sigma^{(-)} \equiv \Sigma^0 - |\Delta\Sigma^{(-)}|$, Figure 3a right upper panel). This allows defining causal ($\Delta\Sigma^{(+)}$) and anti-causal ($\Delta\Sigma^{(-)}$) learning branches, respectively, using sub-100 millisecond pulses (Figure 3b) that, in our case, can be described approximately by:

$$\Delta\Sigma^{(\pm)}(\Delta t) = \begin{cases} \propto \left[+|A_{+,o}| - |A_+|e^{+\frac{\Delta t}{\tau_+}} \right] & \text{for } \Delta t > 0 \\ \propto \left[-|A_{-,o}| + |A_-|e^{-\frac{\Delta t}{\tau_-}} \right] & \text{for } \Delta t < 0 \end{cases} \quad (\text{Equation 1})$$

where $A_{+,o}, A_+, A_{-,o}, A_-$ reflect, respectively, the amplitudes of potentiation and depression and τ_+, τ_- are the corresponding time constants.

Summarizing, our study reveals that the conductance can be accurately increased or decreased by a combination of three basic factors: (i) *time arrival*: if short-wavelength pulses arrive earlier than long-wavelength pulses, the conductance increases with respect to the first pulse (case *i.1*), while the conductance decreases with respect to the first pulse if short-wavelength pulses arrive later than long-wavelength pulses (case *i.2*), (Figures 4a,b); (ii) *cumulated time*: the increase of conductance – case *i.1* – or its decrease – case *i.2* – is modulated by the cumulated time of the light pulses. This is shown in Figures 4a,b where the precise amount of decrease or increase of conductance depends on the duration of the combined pair of pulse trains; (iii) *wavelength*: as shown in Figures 4c-e, for fixed cumulated times, the decrease of conductance in short-/long- wavelength pairs is modulated by the wavelength of the second train of pulses. In particular, the decrease of conductance is largest for second pulses of red light, smaller for green and negligible for blue.

Before proceeding, we make an important observation regarding our approach to time correlations using optical inputs. Our work reveals that if we consider time correlations of optical stimuli that change the synaptic weight between a first (pre-synaptic pulse) and a second (post-synaptic) pulse, a new concept that uses *also* the wavelength of light can be exploited to achieve spiking time dependence plasticity. This concept enables the replication of inhibitory or excitatory synapses encompassing a wide diversity of functional dependences^{26,27} As described below, we propose that these wavelength-sensitive time correlations can be also exploited to use information encoded in light to build spatial memory and navigation maps akin to processes occurring in biological brains, with timescales comparable with biological processes.

DISCUSSION

This application of correlation-based rules is particularly interesting, as it should enable unsupervised learning,¹⁶ which in this case would apply to visual inputs.^{16,25} Indeed, neuron models based on memristive devices that implement STDP have been already demonstrated to show unsupervised learning.^{6, 28} Here we shifted our attention away from known applications of time-correlated synaptic changes to explore alternative possible implementations into new domains. More specifically, we explored the feasibility of exploiting the observed phenomenon to emulate the coexistence of excitatory and inhibitory synapses, which is indispensable to build brain-like cognitive maps.²⁹⁻³¹ As an exemplary illustration, we consider the construction of one-dimensional attractor map models for head direction, in which neuron firing rates evoke the direction along which the head is facing.²⁹ With this in mind, we simulated leaky integrate-and-fire neurons driven asynchronously by two input sensory cells, corresponding to red and violet stimuli (see Experimental Section and Supporting Information for extensive details). Figure 3c shows graphically the time evolution of the synaptic strengths of selected neurons for

two simulated consecutive head movements along two orientations in space. We stress that for the sake of realistic modeling, the calculations take care of the experimental decay times of conductance after photoexcitation with red or violet light pulses (Figure 3a and Figure S5c, Supporting Information). In the simulated process, illumination with violet pulses potentiates the synaptic strength of the small neuron cluster connected to a particular orientation in timescales shorter than 200 ms (Figure 3d). Note that during the transient to a new orientation, red pulses are indispensable to inhibit the strength of synapses unrelated to the new position. Indeed, as shown in Figure 3d (middle panel) and Figure S6 (Supporting Information) the use of red pulses is crucial to speed up the inhibition of firing activity to timescales of a few 100's ms. Finally, Figure 3d displays the firing activity of the simulated neurons for the given threshold of synaptic strength. We stress that although we focus our discussion to two specific wavelengths, our results suggest that the full spectrum can be exploited to achieve causality between pairs of short-/long- wavelength pulses, with varying degrees of intensity of potentiation and depression (Figure S5 and S6, Supporting Information). Based on these observations, we propose that the transcription of optical flow from scenes captured in silicon retinas^{9,10} may be used in the LAO/STO system to emulate cognitive maps from temporally-correlated sensory inputs on the 100's millisecond range, comparable to timescales for perceptual recognition.³²

Before concluding, we hypothesize a mechanism for the observed causality in optical stimuli, which may serve as a guideline for other materials. Crucial to this point is the fact that LAO is a polar material, with a built-in electric field that needs to be compensated to reach stability.^{21,33} One way to achieve this is to generate counteracting dipoles by creating surface and interface charges of opposite signs (Figure 3e, **1**). As pointed out in Ref. 34, this can be accomplished by spontaneous formation of positively charged states (n_s) that transfer electrons to the interface, with a fraction forming the 2DES, while the rest are trapped in negatively

charged defects (n_I). With this in view, we conjecture that the potentiation and depression of photoconductance can be explained by two parallel processes (Figure 3e, [2]). First, we assume that the n_I defects are coupled to phonons forming DX centers,^{17,35} so that lattice relaxation prevents the return of photoexcited electrons from 2DES back to n_I states, leading to PPC (Figure 1a). Alternatively, one may conjecture that the photoexcited electrons are trapped by the confining electrostatic potential of the 2DES. In both cases, the transition rate is proportional to the imaginary part of the dielectric function $\varepsilon_{2,I}(\omega) \propto \{\sum_v |M_v|^2\} n_I \rho_{t_{2g},e_g}(\omega)$, where $|M_v|$ are the transition matrix elements, n_I the density of states (DOS) for interface states and $\rho_{t_{2g},e_g}(\omega)$ the DOS of t_{2g} and e_g levels in the conduction band of STO. We can reasonably expect that, given the typical functional dependence of $\rho_{t_{2g},e_g}(\omega)$,³⁶ photons with shorter wavelengths will be absorbed more intensively (Figure 3e, [2]), which explains the larger PPC as the frequency is increased (Figure 1b). A second process, responsible for the depression of PPC, relies on the photoexcitation of electrons to surface states via quantum tunneling, which neutralize a fraction of the positively charged surface states, thus favoring the transfer of 2DES electrons back to interface states (Figure 3e, [2] and [3]). This mechanism is coherent with the observed modulation of the 2DES transport by changing the surface charge density, e.g., by writing charges with atomic force microscopy tips on the surface of LAO/STO.³⁷ The quantum tunneling-assisted process is proportional to $\varepsilon_{2,II} \propto \{\sum_v |M_v|^2\} n_I n_s e^{-2\left[\frac{2m^*}{h}U\right]d}$, where n_s is the surface state DOS, U and d the LAO energy barrier height and thickness and m^* , h are the effective electron mass and Planck's constant. Therefore, we expect that the relative contribution of process $\varepsilon_{2,II}$ to the optical transitions should be reduced exponentially with d , which is compatible with the experimental data (Figure S9 and Table S1, Supporting Information). Assuming frequency-independence for $\varepsilon_{2,II}$ and recalling the expected larger $\varepsilon_{2,I}$ at shorter wavelengths, the relative weight of $\varepsilon_{2,II}$ versus $\varepsilon_{2,I}$ is increased for longer

wavelengths, which explains why illumination with green and red promote depression of PPC after blue or violet in two-pulse sequences.

In view of this, the spectral response displayed in Figure 2 may depend on the interplay between electrostatic boundary conditions of the LAO layer and the formation energy of interface defects, which require the crystalline structure of LAO (Figure S1). In particular, details of the electronic band structure and vacancy energy formation may depend critically on the epitaxial character of LAO, which would explain the unexpected small spectral response to green light ($\lambda = 520$ nm, Figure 2b). We corroborated this observation by measuring the spectral response of amorphous LAO/STO interfaces, which show that the spectral dependence of the photoconductance is much smoother than that observed in epitaxial samples, with the magnitude of the photoconductance following a gradual evolution across visible wavelengths (Figure S10).

Finally, we note that, as seen in Figure S9 and Table S1 of the Supporting Information, the wavelength-correlated mechanisms that give rise to the time-asymmetric photoresponses become progressively small as the thickness of LAO increases. In other words, the depletion of conductance by two-pulse sequences –in which long-wavelength pulses follow short-wavelength pulses–, disappears gradually. Following this argument, a thickness of LAO just above the critical thickness for conduction (i.e., $4\text{ uc} \approx 1.5\text{ nm}$) yields the maximal asymmetric wavelength-correlated photoresponses, so that time correlations can be best used for possible applications when LAO is grown at such thickness.

CONCLUSION

We conclude by stressing that the results described here may profit from recent developments in artificial vision that, inspired by neurobiology, rely on image acquisition triggered *asynchronously* by per-pixel log-scale changes in brightness, which increase

dramatically the dynamic performance by suppressing data redundancy.^{9,10} We envision that this progress, together with outstanding advances in silicon integrated photonics—including the development of on-chip optical modulators and laser sources—³⁸ provides a unique opportunity to use the kind of time-correlated plasticity described here to expand today’s neuromorphic vision technologies. Interestingly for this context, the creation of two-dimensional electron systems in LAO/STO has been demonstrated on top of silicon.³⁹ Bearing these advances in mind, we envision that integrated electronic/photonic circuitry can be purposely designed to encode optic flow from neuromorphic retinas that can be used to build representation maps reminiscent of those that underpin the ability of self-localization and object motion detection in the brain.²⁹

EXPERIMENTAL SECTION

Sample Preparation. Photoconductance measurements were done in Hall bars defined by optical lithography. For that purpose, we used a sequential deposition method that combines the growth of epitaxial and amorphous LAO layers.⁴⁰ First of all, a layer of polydimethylglutarimide (PGMI) S1813 photoresist was spin-coated on the surface of as-received (001)-oriented $5 \times 5 \text{ mm}^2$ STO crystals (Crystec GmbH) forming a PGMI layer of thickness $\sim 1100 \text{ nm}$ at spin-coating speed of 5000 rpm (Figure S2a, Supporting Information). Subsequently, a Micro-Writer ML3 lithography system was used to expose the PGMI layer by writing directly on it the Hall bar pattern with a $1 \text{ }\mu\text{m}$ laser spot of wavelength $\lambda = 385 \text{ nm}$ and energy fluence 200 mJ/cm^2 . Afterwards, the samples were baked at 75°C for 2 minutes. The exposed areas were then dissolved away by a Shipley MF319 developer to form the Hall bar boundary, leaving behind the unexposed resist with the shape of the Hall bar (Figure S2b, Supporting Information). Subsequently, an amorphous LAO layer of thickness $\sim 60 \text{ nm}$ was deposited at room temperature by pulsed laser deposition ($\lambda = 248 \text{ nm}$) (Figure S2c, Supporting Information). The oxygen partial pressure during the growth was $P_{O_2} = 10^{-4} \text{ mbar}$, the laser repetition rate 1 Hz , the substrate-target distance 55 mm , and the laser pulse energy and fluence of about 26 mJ and 1.5 J/cm^2 , respectively. In the final stage, a lift-off was done with hot acetone to remove the remaining resist together with the

portion of amorphous LAO on top of it (Figure S2d, Supporting Information). The gap left behind was then filled up by growing an epitaxial LAO layer of various thicknesses ranging from 3 to 14 unit cells ($1 \text{ uc} \approx 0.38 \text{ nm}$) (Figure S2e, Supporting Information). During this growth, the oxygen partial pressure was $P_{O_2} = 10^{-4} \text{ mbar}$ and the temperature $T = 650 \text{ }^\circ\text{C}$. At the end of the deposition, the samples were cooled down in oxygen rich atmosphere to minimize the formation of oxygen vacancies, which are known to provide a non-intrinsic contribution to transport in epitaxial LAO/STO interfaces.⁴¹

Using the aforementioned lithography processes, Hall bars were defined with channel widths typically in the range $\sim 5 - 10 \text{ }\mu\text{m}$ and lengths $\sim 80 - 100 \text{ }\mu\text{m}$ (Figure S2a, Supporting Information). The conductive 2DES at the interface only emerges when LAO films are above a critical value^{42,43}. Indeed, the lithography process is designed so that the 2DES is constrained within the Hall bars and, therefore, different Hall bridges defined in a same sample should be ideally isolated electrically. This point was checked out by measuring the resistance between contacts of different Hall bars. We also measured the temperature dependence of the resistance in the Hall bars, showing a metallic behavior all the way down to low temperatures (see one representative data in Figure S3, Supporting Information). The measurements of the carrier density and mobility yielded values $n_s \approx 10^{13} \text{ cm}^{-2}$ and $\mu \approx 1400 \text{ cm}^2/\text{s}$ (at 4 K), respectively, comparable to those reported in the literature.⁴²

Transport characterization under illumination with optical pulses. For the illumination of the samples we used a SpectraTec X system, which includes four lasers of wavelengths 405, 450, 520 and 638 nm. In this equipment, the irradiance of the light at the source output can be regulated electronically by applying voltages in the range 0.5 – 5 V. For this purpose, we used tabulated values provided by the manufacturer to control of the value of irradiance at each wavelength at the exit of the laser source.

Light pulses were controlled by voltage pulses supplied by a Keithley 2611B instrument (Figure 3Sa, Supporting Information). The width and periodicity of the train of pulses could be regulated down to the limit of $5 \mu\text{s}$ with the Keithley TSP Express software.

For transport measurements we used typically dc-currents of $1 \text{ }\mu\text{A}$ supplied by a Keithley 2400 instrument and the voltage along the bridge of the Hall bar was measured by a Lock-in Amplifier (7270 DSP) which was used as a dc-voltmeter with microsecond precision (Figure S4b, Supporting Information).

In order to get the real irradiance that reached the sample, a photodiode detector was used to detect the intensity of the light either directly impinging on the sample or through the confocal microscopic (CFM) lens system (Figure S4c, Supporting Information). The relation between detector signal and input light irradiance is linear (Figure S4d, Supporting Information), from which we can infer the real power density of the light going through the CFM system when the detector signal was measured (Figure S4e, Supporting Information). From these experiments we found that the real power density is almost 1/10 of the irradiance of the light that comes out directly from the laser source (Figure S4f, Supporting Information).

Simulations of neural networks. The simulations of temporally correlated input sensory neurons were performed using the Brian Simulator open source code, which is written in the Python programming language.⁴⁴ We considered the problem of replicating the firing activity patterns of neurons building cognitive maps in the brain. In particular, we focused on attractor map models for head's direction, where a small cluster of neurons spike at a given head orientation. Crucial to this point is the fact that the formation of cognitive maps in biological brains –related to, e.g., spatial memory, self-location and self-motion in the environment require imperatively both excitatory and inhibitory actions on the synaptic strength.^{6,7,32} This prerequisite suits well to the sort of potentiation and depression observed in our experiments using time correlated optical inputs.

ASSOCIATED CONTENT

Supporting Information

Structural characterization, photoconductance induced by illumination with two-pulse sequences, emulation of inhibitory synapses with two-pulse sequences, simulations of neural networks, photoexcitation to surface states via quantum tunneling, reproducibility of photoconductance response, time relaxation of conductance after photoexcitation (PDF).

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Figure 1. a) The persistence photoconductance in terms of the space of configurational coordinates.¹⁸ Before photoexcitation, the electron is in a deep DX center (D).^{18,33} When D is occupied, the strong coupling to the lattice induces a rearrangement of the ion positions in its immediate vicinity, and the strain associated with such distortion is represented by $Q \neq 0$. An incident photon induces an electronic transition from D to the 2DES (C), while a structural lattice relaxation drives a change of the DX center to $Q=0$. The irreversible shift in Q implies an energy barrier (E_a), precluding the return of the electron back to the initial state. The energy levels of the vibronic state of D – corresponding to quantum levels of a harmonic oscillator– are graphically depicted. b) The upper panels display the shape of pulses as detected from light reflected from the surface. The lower panels show the photoconductance measured under illumination with pulses of different wavelengths and irradiance in units of W/cm^2 . c) The upper panels show optical micrographs of a Hall bar. The lower panels show a schematic depiction of the Hall-bar geometry (left) and a cross-sectional graphic view of the LAO/STO device used in the experiments. A-LAO and C-LAO stand, respectively, for amorphous and epitaxial LAO (right) (see the Experimental Section for details on sample and device preparation). d) Sketch of the experimental optical setup.

Figure 2. a) Photoconductance measured under illumination with trains of pulses of different width ($W_p \approx 0.05$ -10 ms) and irradiance (0.25 – 1.25 $/cm^2$). b) Two-dimensional maps where the photoconductive response is mapped against wavelength, irradiance and pulse width. c) and d) show the tunability of the photoconductance by exposing the sample to light pulses of different timespans. In particular, d) shows the changes in photoconductance $\delta\sigma_{ph}(\tau')/\sigma_0$ measured at different probe times ($\tau' = 0, 15, 30$ and 45 s) as a function of the cumulated illumination time. In panels e)-f) we select some of the data shown in previous panels. In particular, e) displays the reflected intensity measured by the photodetector replicating the shape of the incoming light pulses of cumulated times

spanning the range of 5-250 milliseconds. In f) we plot the full time evolution of the photoconductance over the whole period of analyzed time, after illumination with light pulses of cumulated times spanning the range 5-250 milliseconds. The color code identifying the cumulated time in the 5-250 millisecond range is the same as in panel e). The middle panel shows a zoom of the data around the initial times, while the right panel displays the data for a time interval $\approx 156-160$ after the light is switched off.

Figure 3. a) (Left upper panel) Photoconductance measured after a single pulse of red ($\Delta T_r = 60$ ms, red line) and after a two-pulse sequence of red ($\Delta T_r = 60$ ms) plus violet ($\Delta T_v = 40$ ms), purple line. In these experiments, the irradiance was 1.5 W/cm^2 . The two-pulse sequence *increases* the photoconductance from Σ^0 to $\Sigma^0 + |\Delta\Sigma^{(+)}|$. (Right upper panel) The order of the pulse timing is *reversed*: violet pulses ($\Delta T_v = 40$ ms) are followed by red pulses ($\Delta T_r = 0 - 200$ ms); the conductance now *decreases* from Σ^0 to $\Sigma^0 - |\Delta\Sigma^{(-)}|$. The results displayed in a) enable a formal equivalence between red/violet pulse timing and causality of pre- and post-synaptic neurons, as shown schematically in the lower panels. b) Plots the causal ($|\Delta\Sigma^{(+)}(\Delta t)|$) and anti-casual ($|\Delta\Sigma^{(-)}(\Delta t)|$) branches of the learning curve derived from experiments in a). For clarity, the data of the $\Delta\Sigma^{(-)}(\Delta t)$ branch is magnified by 5. Dashed lines in b) are a fitting to Equation 1. Two-pulse sequences are used to simulate a map model for head direction.²⁸ At every orientation, just a small number of synapses are potentiated, while synapses unrelated to that orientation are depressed. c) Radial and linear plots of the calculated synaptic strengths for two head movements (O1 and O2). d) Firing activity (vertical dashed lines) of selected simulated neurons for orientation O1, given the threshold of synaptic strength (dotted horizontal line), stimulated either using a single violet pulse (upper panel) or two-pulse sequences (middle panel). The lower panel displays the activity of a selected neuron for orientation O2. e) Schematics of the two photoexcitation processes that lead to the complementary-wavelength potentiation or depression of photoconductance. [1] The internal electric field E_{int} of the polar LAO layer is partially compensated by the field E_{cmp} created by surface and interface charged defects.³¹ Electrons are transferred from surface states towards the interface, forming the 2DES, while a fraction is trapped in localized interface states. [2] (I) Trapped electrons at the interface are photoexcited towards the 2DES, with more intensity for shorter wavelengths. The photoexcitation is irreversible (Figure 1a), leading to potentiation of PPC. (II) In parallel, electrons are photoexcited towards surface states via quantum tunneling, more efficiently for longer wavelengths. This creates an imbalance between E_{int} and E_{cmp} . [3] This imbalance can be restored by the creation of additional interface and surface defects, promoting the depletion of the 2DES and depression of PPC, which brings the 2DES back to state [1].

Figure 4. The ensemble of panels display the changes $\Sigma^0 \pm |\Delta\Sigma^{(\pm)}|$ of the conductance measured after two-pulse sequences of red ($\Delta T_r = 0 - 95$ ms) plus violet ($\Delta T_v = 0 - 95$ ms). In these experiments, the irradiance was 1.5 W/cm^2 . The value of Σ^0 is set after the first pulse. a) The two-pulse sequence *increases* the photoconductance from Σ^0 to $\Sigma^0 + |\Delta\Sigma^{(+)}|$ when red pulses come before violet. b) When the order of the pulse timing is *reversed*, i.e., violet pulses are followed by red pulses, the conductance *decreases* from Σ^0 to $\Sigma^0 - |\Delta\Sigma^{(-)}|$. The timing and duration of the first and second pulses determine quantitatively the increase or decrease of conductance. Labels R(X)V(Y)/V(Y)R(X) in panels a) and b) display the conductance changes after combined pulses of red and violet light of duration X and Y milliseconds. The measured changes in photoconductance ($\pm|\Delta\Sigma^{(\pm)}|$) are used to plot the causal and anti-causal branches of the plot shown in Figure 3a. Panels c)-e) show the photoconductance measured after a single pulse of violet ($\Delta T_v=40$ ms) followed by red, green and blue pulses of varying duration – ($\Delta T_{(r,g,b)}=0-200$ ms –). Since longer-wavelength pulses come after short-wavelength pulses, the synaptic strength is decreased with respect to the first pulse (we are in the $\Sigma^0 - |\Delta\Sigma^{(-)}|$ anti-causal branch of Figure 3a. Yet, the value of the decrease of conductance ($-|\Delta\Sigma^{(-)}|$) depends on wavelength: the suppression is the largest for red, smaller for green and negligible for blue.