A Cortico-Collicular Model for Multisensory Integration

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Abstract: Remarkable visual-auditory cross-modal phenomena occur at perceptual level: a visual stimulus enhances or biases auditory localization in case of spatially coincident or spatially disparate stimuli. Hemianopic patients (with one blind hemifield resulting from damage to primary visual cortex) retain visual enhancement but not visual bias of auditory localization in the blind hemifield. Here, we propose a neural network model to investigate which cortical and subcortical regions may be involved in these phenomena in intact and damaged conditions. The model includes an auditory cortical area, the primary and extrastriate visual cortices and the Superior Colliculus (a subcortical structure). Model simulations suggest that: i) Visual enhancement of auditory localization engages two circuits (one involving the primary visual cortex and one involving the Superior Colliculus) that act in a redundant manner. In absence of primary visual cortex (hemianopia), enhancement still occurs thanks to the Superior Colliculus strongly activated by the spatially coincident stimuli. ii) Visual bias of auditory localization is due to an additive contribution of the two circuits. In hemianopia, the effect disappears as the Superior Colliculus is not sufficiently activated by the spatially disparate stimuli. The model helps interpreting perceptual visual-auditory phenomena and their retention or absence in brain damage conditions.

1 INTRODUCTION

Perception is a multisensory phenomenon. Everyday environment provides us with a rich flow of information involving various senses simultaneously; our brain combines the different sensory information in order to enhance detection of events, to disambiguate conflicting situations, to produce the most appropriate response (Stein and Meredith, 1993; Calvert, Spence and Stein, 2004). Knowledge of the neural mechanisms underlying cross-modal processing is fundamental for our understanding of human brain functions and a plethora of different techniques (neuroanatomical and electrophysiological in animals, behavioural and neuroimaging in humans) has been used to this aim (Calvert and Thesen, 2004).

A close interconnection between auditory and visual systems has been found in a multitude of subcortical and cortical areas. Among them, the Superior Colliculus (SC) - a subcortical structure involved in orientation and localization behaviour –

has been largely investigated: it receives converging auditory and visual afferents, both from cortical and non-cortical structures, and creates a topographically aligned bimodal representation of the space (Wallace, Meredith and Stein, 1993; Meredith and Stein, 1996). Moreover, compelling evidence now exists that even the primary visual and auditory cortices - traditionally considered to be purely unisensory – exhibit properties of visual-auditory interaction (Ghazanfar and Schroeder, 2006): this may be mediated both via feedback connections from multisensory regions and via direct connections between the unisensory areas (Driver and Spence, 2000; Foxe and Schroeder, 2005).

Such numerous interconnections form the structural basis for the remarkable visual-auditory phenomena observed at perceptual level. In particular, several psychophysical studies have evidenced how visual information can affect the perceived localization of a sound, and two main effects have been observed in healthy subjects. When the visual and auditory stimuli are presented simultaneously at the same spatial position, the

visual cue can improve auditory localization (*visual enhancement of auditory localization*) (Bolognini, Leo, Passamonti, Stein and Làdavas, 2007); the beneficial effect of the visual stimulus is especially evident in case of a weak (i.e., hard-to-localize) sound. This phenomenon could mainly involve the SC, as it is reminiscent of the response properties of SC neurons: the response of a visual-auditory SC neuron is enhanced by spatially coincident stimuli, with less effective unimodal stimuli producing greater response enhancement (a property called *inverse effectiveness*) (Stein and Meredith, 1993). When the visual and auditory stimuli are presented together but in disparate spatial position, the visual cue bias the auditory localization, i.e. sound location is perceived shifted toward the visual stimulus (*visual bias of auditory localization* or *ventriloquism effect*) (Bertelson and Radeau, 1981; Bolognini et al., 2007). This phenomenon may involve direct projections from visual cortex to the auditory cortex (Bertini, Leo, Avenanti and Làdavas, 2010).

The issue of cross-modal visual-auditory processing is receiving growing attention with respect to patients having hemianopia, i.e., a visual field defect, characterized by a loss of vision in one hemifield. It generally results from damage to visual primary cortex (occipital lobe) on one side of the brain, while leaving intact the SC. Studies on these patients (Leo, Bolognini, Passamonti, Stein and Làdavas, 2008; Passamonti, Frissen and Làdavas, 2009) have found that visual enhancement of auditory localization – in case of spatially coincident stimuli - is maintained in the blind hemifield, although the patients may remain unconscious of the visual stimulus. On the contrary, ventriloquism - in case of spatially disparate stimuli - is not retained in the blind hemifield. Retention of enhancement has been hypothesized to depend on the functional integrity of SC and of its related circuits; absence of ventriloquism effect has been explained by the damage of the occipital cortex that disrupts the neural circuits underlying this effect.

Due to the multiplicity of mechanisms and circuits involved, a comprehension of all these aspects may benefit from the use of neural network models. In recent years, we proposed several neurocomputational models to investigate different aspects of visual-auditory integration (Magosso, Cuppini, Serino, Di Pellegrino and Ursino, 2008; Cuppini, Magosso, Rowland, Stein and Ursino, 2012; Magosso, Cuppini and Ursino, 2012; Magosso, Cona and Ursino, 2013; Cuppini, Magosso, Bolognini, Vallar and Ursino, 2014). In particular, some of those models were devoted to

investigate the properties of single neurons in the SC, neglecting aspects of multisensory interaction in the cortex (Magosso et al., 2008; Cuppini et al., 2012); others focused only on visual-auditory integration in the cortex, not including subcortical structures (Magosso et al., 2012, Magosso et al., 2013, Cuppini et al., 2014). Moreover, none of them investigates the mechanisms underlying multisensory perceptual effects in brain damaged patients (such as hemianopic patients). Aim of the present work is to overcome the previous limitations by i) considering, within a single neural network model, the interaction between cortical and subcortical (collicular) areas in visual-auditory processing; ii) mimicking visual enhancement and visual bias of auditory localization in hemianopic conditions, evidencing the differences compared to intact conditions; iii) shading light on the contribution of specific cortical and subcortical circuits in the two examined visual-auditory phenomena.

2 THE NEURAL NETWORK MODEL

2.1 Model Description

The model includes four areas of neurons (Fig. 1), representing: the auditory cortex (A), the primary visual cortex (V), the extrastriate visual cortex (E), the Superior Colliculus (SC). The external auditory stimulus impacts on area A, which is reciprocally connected with area SC. The external visual stimulus targets area V (this mimics the geniculo-striatal pathway), which communicates with area E; the visual stimulus also impacts directly the SC (this mimics the retino-collicular pathway). Area V and E are also connected with SC. Finally, the two areas A and V communicate directly via reciprocal synapses.

Each area is formed by a monodimensional array of N ($N = 181$) neurons, which code for the azimuth positions of the external space and are topologically aligned (proximal neurons code for proximal positions). We assumed that the head and eyes of our hypothetical subject are fixed and maintained in central alignment, so that the head-centered coordinates (for auditory space coding) and the retinotopic coordinates (for visual space coding) are coincident. These conditions are the same adopted in psychophysical studies investigating visual enhancement and bias of auditory localization (Leo et al., 2008). Azimuthal positions range between -

90° and +90°, and are spaced 1° apart so that both hemifields of space are represented (one spanning from -90° to -1°, the other from +1° to +90°, 0° representing the central position). Finally, neurons within each area communicate via lateral synapses.
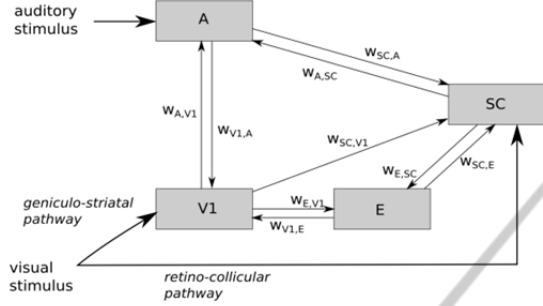

Figure 1: Model architecture.

In the following, each neuron is referenced with a superscript (r) indicating its area ($r = A, V, E, SC$) and subscript (j) indicating its position within the area ($j = -90° \div +90°$, i.e., its preferred azimuth position). $u(t)$ represents the net input of a neuron at time t and $y(t)$ represents its output activity.

The activity $y_j^r(t)$ of a generic neuron is computed by feeding its input $u_j^r(t)$ through a sigmoidal function (saturated to 1) and a first order dynamics. To include variability in the network, the sigmoidal function is affected by Poisson random noise. For the sake of simplicity, we used the same time constant and the same sigmoidal relationship for all types of neurons.

The net input $u_j^r(t)$ that reaches a neuron may be generically written as the sum of three contributions: an *external input* $\varphi_j^r(t)$ due to a stimulus (visual or auditory) in the space, a *lateral input* $\lambda_j^r(t)$ coming from other neurons in the same area via lateral synapses, an *inter-area input* $\varepsilon_j^r(t)$ coming from neurons in the other areas via inter-area synapses. Hence, we can write

$$u_j^r(t) = \varphi_j^r(t) + \lambda_j^r(t) + \varepsilon_j^r(t) \qquad (1)$$

where each term can assume a different expression according to the specific area. Expressions for individual term in (1) are given below.

i) The external input - Area A, area V and area SC receive an external input (see Fig. 1). The external input is mimicked via a Gaussian function, representing the result of a local stimulus spatially filtered by the neuron receptive fields (RFs)

$$\varphi_j^r(t) = \varphi_0^r \cdot \exp\left(-\frac{(j - p^r)^2}{2 \cdot (\sigma^r)^2}\right), r = A, V, SC \quad (2)$$

p^r is the position at which the stimulus is centered; $p^V = p^{SC}$ since the same visual stimulus impacts simultaneously on both the areas. σ^r is related to the width of neuron RF: we set $\sigma^V = \sigma^{SC}$; moreover, to simulate the higher spatial resolution of the visual system, we assumed that $\sigma^V (= \sigma^{SC})$ is smaller than σ^A (Magosso et al., 2012). φ_0^r represents the strength of the stimulus (arbitrary units): since the SC receives less fibres from the retina than the primary visual cortex (Cowey, 2010), we set $\varphi_0^{SC} = 0.5 \cdot \varphi_0^V$.

Finally, the exstrastriate area (E) does not receive any external input, hence

$$\varphi_j^E(t) = 0, \forall j \qquad (3)$$

ii) The lateral input - This input originates from the lateral connections within the same area, and it is computed as

$$\lambda_j^r(t) = \sum_k L_{jk}^r \cdot y_k^r(t), r = A, V, E, SC \qquad (4)$$

L_{jk}^r is the strength of the lateral synapse from a presynaptic neuron at position k to the postsynaptic neuron at position j, both in the same area r, and $y_k^r(t)$ is the activity of the presynaptic neuron. In each area, lateral synapses are arranged according to a Mexican hat, obtained as the difference of excitatory and inhibitory contributions, each mimicked as a Gaussian function. Autoexcitation and autoinhibition are avoided in each area.

iii) The inter-area input The inter-area input originates from inter-area synapses. For the sake of simplicity, inter-area synapses have a one-to-one structure (i.e., they connect neurons in spatial register). According to Fig. 1, we have

$$\begin{aligned}
\varepsilon_j^A(t) &= w_{A,V} \cdot y_j^V(t) + w_{A,SC} \cdot y_j^{SC}(t) \\
\varepsilon_j^V(t) &= w_{V,A} \cdot y_j^A(t) + w_{V,E} \cdot y_j^E(t) \\
\varepsilon_j^E(t) &= w_{E,V} \cdot y_j^V(t) + w_{E,SC} \cdot y_j^{SC}(t) \\
\varepsilon_j^{SC}(t) &= w_{SC,V} \cdot y_j^V(t) + w_{SC,E} \cdot y_j^E(t) \\
&\quad + w_{SC,A} \cdot y_j^A(t)
\end{aligned} \qquad (5)$$

where $w_{r,s}$ is a parameter indicating the strength of connection from a neuron in area s to a neuron in area r.

Parameter values were assigned according to the following criteria. i) *Parameters of the external input* - Standard deviations were set so that the visual stimulus induces a narrow activation, while an auditory stimulus induces a wider excitation compatible with visual bias of sound location (Alais et al. 2010). Strength of the input to area V and A was assigned so that neuron response settles to the lower part or central (linear) part of the sigmoidal

static characteristic. Strength of the external visual input to SC was assigned sufficiently low so that it is unable to effectively activate SC in absence of cortical input (Sparks, 1986). ii) *Parameters of individual neurons* – Parameters of the sigmoidal relationship was assigned to have a smooth transition from silence to saturation. The dynamic resembles that of neuron membrane (Magosso et al., 2012). iii) *Parameters of lateral intra-area syna*pses – They parameters were assigned to maintain confined activation in each area preventing excessive spreading of excitation. iv) *Parameters of inter-area synapses* – They were assigned so that : a) an unimodal effective stimulus does not induce a phantom activation in the areas of non-stimulated modality; b) an unimodal effective stimulus induces an intermediate level of activation in the SC neurons.

2.2 Model Simulations and Computation of Model Outcome

The model was used to simulate hemianopic conditions. A hypothetical hemianopic patient was simulated by silencing 80 neurons, randomly chosen, in the hemifield $+1° \div +90°$ within the primary visual area (area V). Moreover, the spared V neurons in this hemifield were made less sensitive to input by modifying their sigmoidal function. We will refer to hemifield $+1° \div +90°$ as the *hemianopic field*. The hemifield $-1° \div -90°$ was maintained intact; we will refer to it as *intact field*.

Simulations were performed by stimulating the network with unimodal (auditory or visual) stimuli and bimodal visual-auditory stimuli (both spatially coincident and spatially disparate), in the intact and hemianopic field. Stimuli were applied at the beginning of the simulation and maintained throughout. Each simulation lasted enough to reach regime conditions.

To evaluate visual enhancement and visual bias of auditory localization in the model, we calculated a quantity representing the perceived location of the auditory stimulus starting from the overall auditory population activity. At the end of simulation, we computed the average value, i.e. the barycenter (b^A), and the standard deviation (s^A) of the population activity in area A

$$b^A = \frac{\sum_j y_j^A \cdot j}{\sum_j y_j^A} \quad (6)$$

$$s^A = \sqrt{\frac{\sum_j y_j^A \cdot (j - b^A)}{\sum_j y_j^A \cdot j}} \quad (7)$$

The perceived auditory location l^A was obtained as:

$$l^A = b^A + n_s^A \quad (8)$$

where the barycenter metric is affected by a random Gaussian noise (n_s^A) with null mean and standard deviation equal to s^A.

Then, according to psychophysical studies, we computed the auditory localization error

$$|l^A - p^A| \quad (9)$$

and the visual bias of auditory location

$$\frac{l^A - p^A}{p^V - p^A} \cdot 100 \quad (10)$$

where p^A and p^V represent the actual position of the auditory and visual stimulus, respectively.

3 RESULTS

We first present network response to unimodal stimulation, in order to describe network behavior. Then visual enhancement and visual bias of auditory localization were analyzed in both hemifields.

3.1 Unimodal Stimulation

Fig. 2 shows the exemplary network response to an unimodal visual stimulus applied in the intact field (at position p^V = -40°, Fig. 2 (a)) and in the hemianopic field (p^V = + 40°, Fig. 2 (b)) of a simulated hemianopic patient. In both cases, the strength of the stimulus is φ_0^V = 16. In the intact field, the visual stimulus is effective enough to highly activate both the primary and extrastriate visual areas, and to produce an intermediate activation in the SC. Activation of both visual cortices may correspond to conscious perception of the visual stimulus. No phantom activation in the auditory area is produced by a single visual stimulus. In the hemianopic field, the visual stimulus produces a very mild activation of spared V neurons close to that position, while extrastriate area remains silent. Lack of activation in these areas may reproduce visual unawareness. The direct retino-collicular pathway activates SC neurons just above threshold.

Fig. 3 displays the response to an unimodal auditory stimulus; this response is the same in the two hemifields as it does not involve the visual pathways. A stronger (φ_0^A = 17, Fig. 3 (a)) and a weaker (φ_0^A = 15, Fig. 3 (b)) auditory stimulus is applied to the network at p^A= -40°. The stronger auditory stimulus induces a high and quite confined
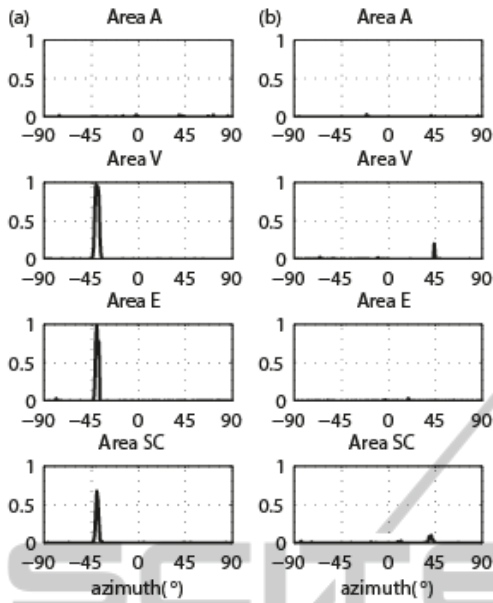
Figure 2: Unimodal visual stimulation. (a) Neuron activity in the model areas in response to a visual stimulus of strength φ_0^V=16 applied in the intact field (p^V=-40°). (b) Neuron activity in the model areas in response to a visual stimulus of strength φ_0^V=16 applied in the hemianopic.
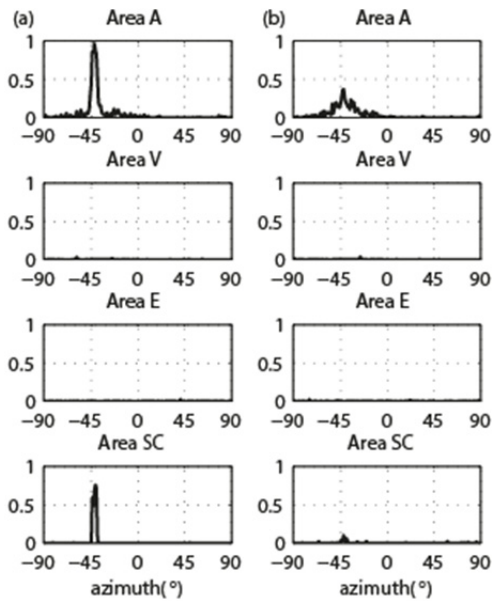

Figure 3: Unimodal auditory stimulation. (a) Neuron activity in the model areas in response to an auditory stimulus of strength φ_0^A=17. (b) Neuron activity in the model areas in response to an auditory stimulus of strength φ_0^A=15.

activation in the auditory cortex and activation of the SC; this may correspond to an easy-to-localize sound. The weaker stimulus produces a low and

spread activation in the auditory cortex, and an extremely low activation in the SC; this may correspond to a hard-to-localize sound. Worth noticing that an effective auditory stimulus does not produce any phantom activation in the visual areas.

3.2 Visual Enhancement of Auditory Localization

The weak auditory stimulus ($\varphi_0^A = 15$) has been applied together with the visual stimulus ($\varphi_0^V = 16$) in the same spatial position, both in the intact hemifield ($p^A = p^V = -40°$) and in the hemianopic hemifield ($p^A = p^V = +40°$). Results are reported in Fig. 4.

In the intact field (Fig.4 (a)), the bimodal stimulation induces a strong activation in all the areas. In particular, activation in area A is strongly heightened and narrowed compared to unimodal condition (compared with Fig. 3 (b)): this mimics the perceptual enhancement of auditory localization. Two mechanisms may contribute to such an enhancement: i) the direct synapses between area A and V; ii) the feedback synapses entering the auditory neurons from the SC. In the hemianopic field (Fig.4 (b)), combination of the two stimuli (which - when applied separately - produce just a minimum activation in SC) triggers SC neurons to the maximum level. This is the consequence of the sigmoidal activation function of the neuron: the two stimuli together move the working point of SC neurons along the steep central part of the sigmoid, causing a disproportionate increase in the response (inverse effectiveness). Strong SC activation, via the feedback synapses, reinforces auditory activity in a spatially selective manner; just a weak improvement of activation in area V and E occurs that could not be sufficient for emergence of visual awareness. This may correspond to enhancement of auditory localization by an "unseen" visual stimulus.

To quantify the visual enhancement of auditory localization and to resembles the procedure adopted in real psychophysical studies (Leo et al., 2008), ten hemianopic patients were simulated (by randomly silencing 80 neurons in the hemianopic field): in each simulated patient, fifteen weak auditory unimodal stimulations (as in Fig. 3 (b)) and fifteen spatially coincident bimodal stimulations (as in Fig. 4) were applied at each of the following positions ±24°, ±40°, ±56°. For each stimulation, the localization error was calculated according to (9) and data were collapsed across positions in each hemifield. Moreover, in order to discriminate the role of the SC and the role of area V in the
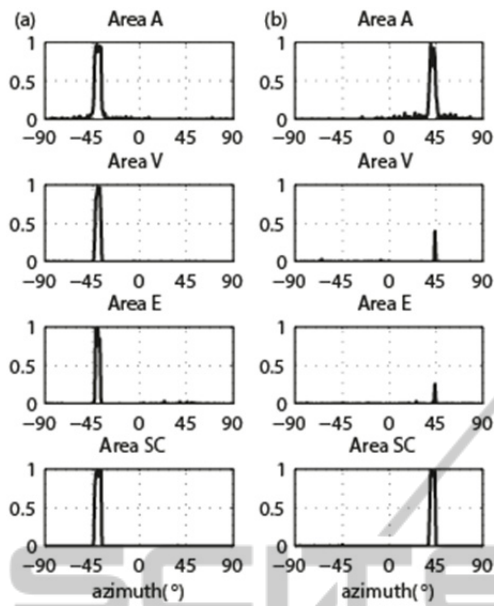
Figure 4: Bimodal spatially coincident stimulation. Neuron activity in the model areas in response to a visual stimulus of strength φ_0^V=16 and an auditory stimulus of strength φ_0^A=15. (a) Stimuli applied in the intact field ($p^V=p^A$=-40°). (b) Stimuli applied in the hemianopic field ($p^V=p^A$=40°).
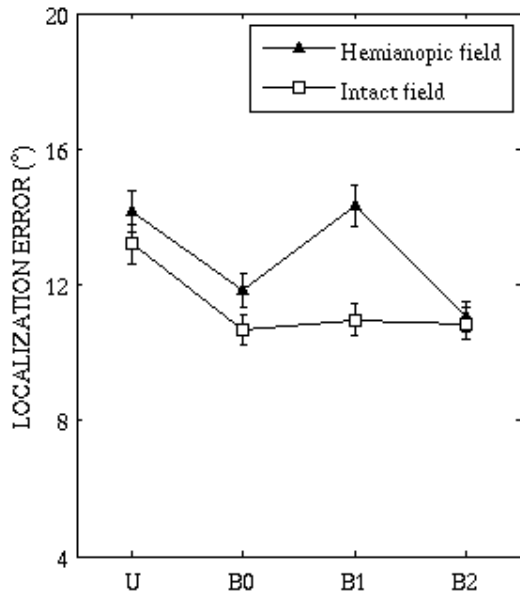

Figure 5: Auditory localization error. U: unimodal auditory stimulation. B0 bimodal stimulation. B1: bimodal stimulation with $w_{A,SC}=w_{E,SC}=0$. B2: bimodal stimulation with $w_{A,V}=w_{V,A}=0$.

enhancement effect, in case of bimodal stimulation, the localization error was computed in three different conditions: with all intact synapses, by neglecting the feedback synapses exiting the SC ($w_{A,SC}=w_{V,SC}=0$), by neglecting the direct visual-auditory synapses ($w_{A,V}=w_{V,A}=0$). Results are reported in Fig. 5. Both in the intact and in the hemianopic fields, the auditory localization error in bimodal condition is significantly reduced with respect to unimodal condition (in agreement with in-vivo studies (Leo et al., 2008)). Interestingly, in the intact field, direct visual-auditory synapses and the SC feedback synapses play a redundant role, as their selective elimination does not impact significantly on error reduction. Conversely, in the hemianopic field, the residual circuit involving the SC becomes essential for the enhancement to occur.

3.3 Visual Bias of Auditory Localization

Fig. 6 displays network response to the visual stimulus and the simultaneous weak auditory stimulus applied 16° left, in the intact field (Fig. 6 (a)) and in the hemianopic field (Fig. 6 (b)). In the intact field, the effective visual stimulus strongly reinforces the marginal auditory activation at the visual stimulus position; such auditory neurons are just above threshold and can be positively reinforced both via the direct visual– auditory synapses and via the feedback from the SC (strongly activated at the
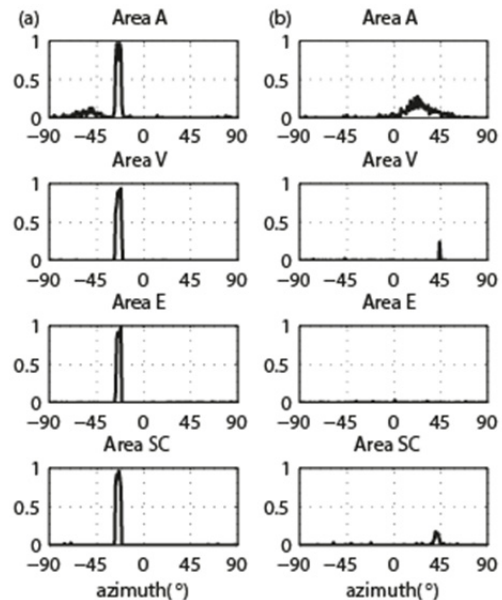

Figure 6: Bimodal spatially disparate stimulation. Neuron activity in the model areas in response to a visual stimulus of strength φ_0^V=16 and an auditory stimulus of strength φ_0^A=15. (a) Stimuli applied in the intact field (p^V=-24, p^A=-40°). (b) Stimuli applied in the hemianopic field (p^V=40, p^A=24°).

visual stimulus position). Hence, the auditory activation is biased toward the location of the visual stimulus. On the contrary, in the hemianopic field, no significant alteration in the auditory activation can be observed with respect to unimodal condition (see Fig. 3 (b)). Worth noticing that in this case, SC neurons are only slightly activated (by the direct visual input) since the two weak stimuli, being spatially disparate, do not have an enhancement effect on the SC neurons.

To quantify the visual bias of auditory localization - in each simulated patient – a visual stimulus was applied (fifteen times) at each of the following locations ±24°, ±40°, ±56°, together with a weak auditory stimulus located 16° right or left. For each stimulation, visual bias was computed according to (10) and results were collapsed across positions in each hemifield. In the intact hemifield, simulations were performed with all intact synapses and by selectively removing the feedback synapses from the SC and the direct-visual auditory synapses. Results are displayed in Fig. 7. According to in vivo data (Leo et al., 2008), in the intact field (with all intact synapses) visual bias is about 40% of visual-auditory disparity; the SC feedback synapses and the direct visual-auditory synapses cooperate in a balanced manner to produce the effect. In the hemianopic field, the visual bias is irrelevant.
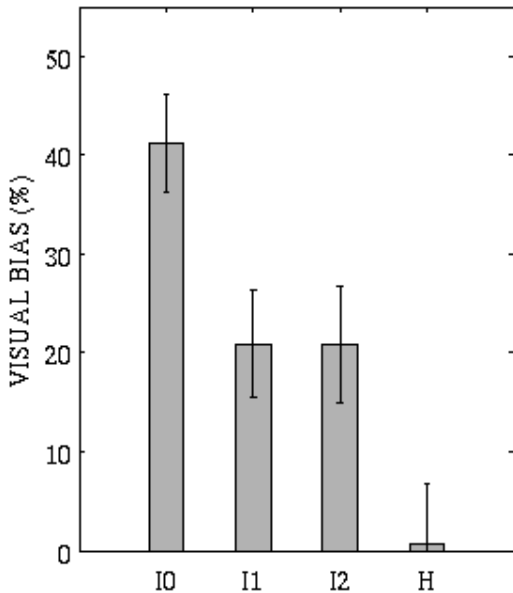

Figure 7: Visual bias of auditory localization. I0: stimulation within intact field. I1 stimulation within intact field with $w_{A,SC} = w_{E,SC} = 0$. I2: stimulation within intact field with $w_{A,V} = w_{V,A} = 0$. H: stimulation within hemianopic field.

4 DISCUSSION

Here, we propose a model that considers the interaction between cortical and subcortical structures (i.e., the Superior Colliculus) in mediating visual-auditory perceptual phenomena. The model represents an extension of our previous models (Magosso et al., 2008; Cuppini et al., 2012; Magosso et al., 2012; Magosso et al., 2013; Cuppini et al., 2014). Some main advancements can be highlighted. i) The neural network includes a distinction between the primary and the extraprimary visual cortices and their different interactions with the SC. Such distinction was neglected in the previous models, while it may be important in investigating visual deficits that selectively involve specific part of the visual pathway. ii) The model investigates how the interaction between cortical and subcortical circuits may affect cortical activation and may reflect at perceptual level. Previous models, on the contrary, either inspected only properties of single SC neurons, without considering perceptual effects mediated by the cortex, or investigated perceptual illusions by modeling only cortical areas and neglecting the cortical-collicular communication; iii) Previous models did not investigated multisensory effects in brain damaged patients.

Model architecture agrees with existing knowledge in the literature. It includes two major visual pathways (Tong, 2003; Isa and Yoshida, 2009): one (geniculo-striatal pathway) guides most of the projections from the retina - via the geniculus- to the primary visual cortex, which communicates with the extrastriate area; the other (retino-collicular pathway) sends a smaller number of projections from the retina directly to SC. In agreement with several studies (Sparks, 1986; Wallace et al., 1993 Meredith and Stein, 1996; Stein and Meredith, 1993), model SC neurons receive afferents from the visual cortical areas (areas V and E), and from the auditory cortical area, and have visual and auditory RF in spatial register. The property of inverse effectiveness of real multisensory SC neurons (Stein and Meredith, 1993) is mimicked via the non-linear (sigmoidal) activation function. Moreover, SC area in the model sends feedback connections to area A and area E: according to neuroanatomical data (Isa and Yoshida, 2009; Sparks, 1986). Finally, the model includes direct synapses between area A and V in agreement with evidence of direct connections between unisensory areas (Alais, Newell and Mamassian, 2010; Foxe and Schroeder, 2005)..

Network activation is interpreted in terms of perceptual responses. First, we hypothesized that a

visual stimulus is consciously perceived only in case of simultaneous and sufficiently high activation in both area V and E. This is in agreement with some theories of visual awareness (Tong, 2003). Second, we assumed that the perceived location of an auditory stimulus is "read out" from the population auditory activity as the barycenter of activity, affected by a noise proportional to the dispersion of activity around the barycenter. This provides auditory localization error in agreement with in-vivo data (Leo et al., 2008; Bolognini et al., 2007).

The model is used to inspect the circuits underlying the phenomena of visual enhancement and visual bias of auditory localization The following speculations can be drawn from model results. i) In intact conditions, visual enhancement of auditory localization is mediated by two mechanisms: the feedback synapses from the SC and the direct visual-auditory synapses. These mechanisms are redundant. Indeed, the spatially coincident stimuli produce a strong activation (up to maximum level) both in area V and in area SC: the synapses entering auditory area from either area V or area SC are sufficient by themselves - joined with lateral synapses in area A - to reinforce auditory activation up to saturation level and to narrow it. Hence, each single mechanism is maximally effective. ii) Such redundancy has enormous benefit in hemianopic conditions in which area V has lost its functionality. The residual mechanism, i.e. the feedback from the SC, gives rise to an effect which is comparable to that observed in intact condition (Fig. 5). It is important to note that this strongly depends on SC neurons robust activation, which is the consequence of the spatial rule and the inverse effectiveness rule implemented in the model. iii) The retention of this effect in hemianopia occurs also in the absence of significant activation in the visual areas (Fig. 4 (b)), corresponding to absence of awareness of the visual stimulus (as in vivo study (Leo et al., 2008)). iv) In intact condition, visual bias of auditory localization results from the additive influence of direct visual-auditory synapses and of the SC feedback synapses; the two mechanisms contribute to a similar extent to the final bias. v) In hemianopic condition, the spared SC circuit is not able to maintain its effect: because of the spatial disparity between the visual and auditory stimulus, the overall input reaching the SC neurons is not sufficient to enhance their activity.

In conclusion, the model provides insight into the contributions of cortical and subcortical circuits in mediating visual-auditory phenomena and interprets the retention or absence of these

phenomena in hemianopic patients. We would like to mention some important aspects, not considered here, that can be the subject of future extensions. 1) Simulation of audio-visual integration in neglect patients. Neglect patients suffered of a visual attentional deficit due to a lesion in the fronto-temporal parietal areas (extraprimary areas, e.g. area E in our model), hence residual multisensory integration in these patients may be mediated by different circuits compared to hemianopic patients. 2) Simulation of motivational factors (e.g. reward expectation) on cross-modal binding. Recent studies (Bruns, Maiworm and Röder, 2014) , indeed, have evidenced that participant's motivational goal significantly influences ventriloquism effect. 3) Simulation of gaze mechanisms. Here, we considered only condition of fixed head and eyes and did not simulated conditions of visual exploration of space. Oculomotor strategies are particularly important for visual localization in hemianopic patients. 4) Simulation of rehabilitation of hemianopic patients via visual-auditory integration. Indeed, some studies (Bolognini, Rasi, Coccia and Làdavas, 2005) have proved that hemianopic patients, subjected to an audio-visual stimulation training, improved visual field exploration and visual detections.

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REFERENCES

Alais, D., Newell, F.N., and Mamassian, P., 2010. Multisensory processing in review: from physiology to behaviour. *Seeing and Perceiving*, 23(1), pp.3–38.

Bertelson, P., and Radeau, M., 1981. Cross-modal bias and perceptual fusion with auditory-visual spatial discordance. *Perception & Psychophysics*, 29(6), pp.578–584.

Bertini, C., Leo, F., Avenanti, A., and Làdavas, E., 2010. Independent mechanisms for ventriloquism and multisensory integration as revealed by theta-burst stimulation. *The European Journal of Neuroscience*, 31(10), pp.1791–1799.

Bolognini, N., Rasi, F., Coccia, M. Làdavas, E., 2005. Visual search improvement in hemianopic patients

after audio-visual stimulation. *Brain*, 128 (Pt.12), pp. 2830-2842.

Bolognini, N., Leo, F., Passamonti, C., Stein, B.E., and Làdavas, E., 2007. Multisensory-mediated auditory localization. *Perception*, 36(10), pp.1477–1485.

Bruns, P., Maiworm, M., Röder, B., 2014. Reward expectation influences audiovisual spatial integration. *Attention, Perception & Psychophysics*, [Epub ahead of print].

Calvert, G., Spence, C., and Stein, B.E., 2004. *The handbook of multisensory processes*. MIT Press.

Calvert, G., and Thesen, T., 2004. Multisensory integration: methodological approaches and emerging principles in the human brain. *Journal of Physiology, Paris*, 98(1-3), pp.191–205.

Cowey, A., 2010. The blindsight saga. *Experimental Brain Research*, 200(1), pp.3–24.

Cuppini, C., Magosso, E., Rowland, B., Stein, B., and Ursino, M., 2012. Hebbian mechanisms help explain development of multisensory integration in the superior colliculus: a neural network model. *Biological Cybernetics*, 106(11-12), pp.691–713.

Cuppini, C., Magosso, E., Bolognini, N., Vallar, G., and Ursino, M., 2014. A neurocomputational analysis of the sound-induced flash illusion. *Neuroimage*, 92, pp.248-266.

Driver, J., and Spence, C., 2000. Multisensory perception: beyond modularity and convergence. *Current Biology*, 10(20), pp.R731–735.

Foxe, J.J., and Schroeder, C.E., 2005. The case for feedforward multisensory convergence during early cortical processing. *Neuroreport*, 16(5), pp.419–423.

Ghazanfar, A.A., and Schroeder, C.E., 2006. Is neocortex essentially multisensory? *Trends in Cognitive Sciences*, 10(6), pp.278–285.

Isa, T., and Yoshida, M., 2009. Saccade control after V1 lesion revisited. *Current Opinion in Neurobiology*, 19(6), pp.608–614.

Leo, F., Bolognini, N., Passamonti, C., Stein, B.E., and Làdavas, E., 2008. Cross-modal localization in hemianopia: new insights on multisensory integration. *Brain*, 131(Pt 3), pp.855–865.

Magosso, E., Cona, F., and Ursino, M., 2013. A neural network model can explain ventriloquism aftereffect and its generalization across sound frequencies. *BioMed Research International*, 2013, p.475427.

Magosso, E., Cuppini, C., Serino, A., Di Pellegrino, G., and Ursino, M., 2008. A theoretical study of multisensory integration in the superior colliculus by a neural network model. *Neural Networks*, 21(6), pp.817–829.

Magosso, E., Cuppini, C., and Ursino, M., 2012. A neural network model of ventriloquism effect and aftereffect. *PLoS ONE*, 7(8), p.e42503.

Meredith, M.A., and Stein, B.E., 1996. Spatial determinants of multisensory integration in cat superior colliculus neurons. *Journal of Neurophysiology*, 75(5), pp.1843–1857.

Passamonti, C., Frissen, I., and Làdavas, E., 2009. Visual recalibration of auditory spatial perception: two separate neural circuits for perceptual learning. *The European Journal of Neuroscience*, 30(6), pp.1141–1150.

Sparks, D.L., 1986. Translation of sensory signals into commands for control of saccadic eye movements: role of primate superior colliculus. *Physiological Reviews*, 66(1), pp.118–171.

Stein, B.E., and Meredith, M.A., 1993. *The merging of senses*. Cambridge, MA, The MIT Press.

Tong, F., 2003. Cognitive neuroscience: Primary visual cortex and visual awareness. *Nature Reviews Neuroscience*, 4(3), pp.219–229.

Wallace, M.T., Meredith, M.A., and Stein, B.E., 1993. Converging influences from visual, auditory, and somatosensory cortices onto output neurons of the superior colliculus. *Journal of Neurophysiology*, 69(6), pp.1797–1809.