Spatial context in the early visual system

Lauri Nurminen

Institute of Behavioural Sciences,
University of Helsinki,
Finland

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Supervisors: Docent Simo Vanni, MD, PhD
Brain Research Unit
O.V. Lounasmaa Laboratory
School of Science
Aalto University
Espoo, Finland

Professor Jussi Saarinen, PhD
Institute of Behavioural Sciences
University of Helsinki
Helsinki, Finland

Reviewers: Professor Timothy Meese, PhD
School of Life and Health Sciences
Aston University
Birmingham, UK

Docent Iiro Jääskeläinen, PhD
Brain and Mind Laboratory, Department of Biomedical Engineering and Computational Science
School of Science
Aalto University
Espoo, Finland

Opponent: Professor Robert Hess, PhD
Department of Ophthalmology
McGill University
Montreal, Canada

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Abstract

Important visual objects in our everyday life, such as fellow people, passing cars or birds perhaps, are not point-like structures but often occupy considerable amounts of the visual field. However, each photoreceptor in our eyes samples just a tiny portion of the visual field and somehow the visual system should integrate these local signals. This process takes place mainly in the visual cortex and, while higher-order visual areas play an important role in perception of extended structures, it is now well established that visual neurons at the first cortical steps of seeing integrate broad spatial context into their responses. The main purpose of this thesis was to provide detailed information concerning the spatial structure of the mechanisms that underlie integration of spatial context in the early visual system.

The opening study of this thesis showed that the antagonistic Gaussians structure that has been used for modeling context integration in single visual neurons provides a relatively accurate description of the process also in the human visual system. The first study introduced a novel method for connecting perceptual and neuroimaging measurements and this method was applied in the second study of this thesis. The second study showed that the human visual system integrates spatial context in terms of its visual field size instead of the size of its cortical representation. The third study showed that context is integrated over an unexpectedly large region of the visual field and that spatially distant context may sometimes increase the contrast response of the visual system. The closing study showed that orientation specificity of the integration of spatial context depends on distance both in single neurons in the macaque primary visual cortex and in human perception.

The knowledge acquired in this thesis will be generally useful in applications that require understanding of the human visual system.

Tiivistelmä

Arkielämän kannalta tärkeät visuaaliset objektit kuten ihmiset, ohikiitävät autot ja kenties kissat, ovat harvoin pistemäisiä, mutta sen sijaan voivat peittää laajankin alueen näkökentästä. Näköaistinsolut prosessoivat kuvainformaatiota erittäin pieneltä näkökentän alueelta ja näköjärjestelmän tulee jollain tavoin yhdistää nämä paikalliset signaalit. Vaikka näköaivokuoren myöhäisten alueiden merkitys spatiaalisesti laajojen objektien havaitsemisessa onkin merkittävä, nykytietämyksen valossa on kiistatonta että myös varhaisten näköaivokuorten hermosolut integroivat spatiaalista kontekstia laajalta näkökentän alueelta. Tässä väitöskirjassa tutkitaan konteksti-integraation taustalla olevien mekanismien spatiaalista rakennetta varhaisessa näköjärjestelmässä.

Väitöskirjan ensimmäisessä osatyössä osoitettiin että konteksti-integraatiota yksittäisissä hermosoluissa kuvaavat kahden antagonistisen Gaussilaisen mallit ovat melko hyviä kuvauksia konteksti-integraatiomekanismien spatiaalisesta rakenteesta myös ihmisen näköjärjestelmässä. Ensimmäisessä osatyössä kehitettiin menetelmä joka mahdollistaa havainto- ja aivokuvantamismittausten uudenlaisen yhdistämisen. Tätä menetelmää sovellettiin toisessa osatyössä, jonka päätulos oli konteksti-integraation riippuvuus ärsykkeen koosta näkökentässä sen sijaan että se olisi sidoksissa ärsykkeen edustuksen kokoon aivokuorella. Kolmannessa osatyössä osoitettiin, että kontekstia integroidaan huomattavan laajalta alueelta ja että spatiaalisesti etäinen konteksti saattaa toisinaan vahvistaa näköjärjestelmän kontrastivastetta. Neljäs tutkimus osoitti, että konteksti-integraation valikoivuus orientaatiolle riippuu etäisyydestä niin ihmisen näköhavainnoissa kuin makaki-apinan ensimmäisen näköaivokuoren soluissakin.

Tämän väitöskirjan tuloksia voidaan hyödyntää sovelluksissa joissa tarvitaan tietoa ihmisen näköjärjestelmän toiminnasta.

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List of original publications

Study I
Nurminen, L., Kilpeläinen M., Laurinen, P. & Vanni, S. (2009) Area summation in human visual system: psychophysics, fMRI and modeling. *J Neurophysiol*, 102, 2900-2909

Study II
Nurminen, L., Kilpeläinen M. & Vanni, S. (2013) Fovea-periphery axis symmetry of surround modulation in the human visual system. *PLoS ONE,* 8(2): e57906

Study III
Nurminen, L., Peromaa, T. & Laurinen, P. (2010) Surround suppression and facilitation in the fovea: Very long-range spatial interactions in contrast perception. *J Vis*, 10, article 9

Study IV
Shushruth, S., Nurminen, L., Bijanzadeh, M., Ichida, J., Vanni, S. & Angelucci A. (2013) Different orientation tuning of near- and far-surround modulation in macaque primary visual cortex mirrors their tuning in human perception. *J Neurosci,* 33, 106-119

Abbreviations

BOLD	Blood oxygen level dependent
CRF	Classical receptive field
CRT	Cathode ray tube
ECRF	Extra-classical receptive field
EPI	Echo planar imaging
(f)MRI	(functional) magnetic resonance imaging
LGN	Lateral geniculate nucleus
VSD	Voltage sensitive dye
V1	Primary visual cortex
V2	Secondary visual cortex

1. Introduction

1.1 The early visual system

Processing of visual information begins in the retina wherein photoreceptors convert light energy into electrical signals in a process called phototransduction (Burns & Lamb, 2004). The photoreceptor signals are processed by a network of horizontal, amacrine and bipolar cells before retinal ganglion cells transmit the signals away from the retina. The balanced and antagonistic center-surround receptive field structure of the retinal ganglion cells (Barlow, 1953) assures that ganglion cells transmit spatial variations in the input image instead of a perfect reconstruction (Rodieck & Stone, 1965).

Axons of the retinal ganglion cells project mainly to the lateral geniculate nucleus (LGN) of the thalamus (Callaway, 2005). The parvocellular pathway, which conveys fine grained spatial information and has relatively low contrast sensitivity, terminates at the four most dorsal layers of the LGN (Kaplan, 2004). The magnocellular pathway with low spatial resolution, high contrast sensitivity and fast signal conduction velocity terminates at the two most ventral layers (Kaplan, 2004). The less well understood koniocellular pathway terminates below each magnocellular and parvocellular lamina (Kaplan, 2004). The magnocellular pathway projects to layer 4Cα and parvocellular pathway to layer 4Cβ of the primary visual cortex (V1) (Livingstone & Hubel, 1988), but the pathways are most probably mixed beyond the input layers (Sincich & Horton, 2005).

While neural responses in the lateral geniculate nucleus are largely insensitive to stimulus orientation, marked orientation tuning emerges in the primary visual cortex (Hubel & Wiesel, 1959). Hubel and Wiesel (1962) suggested that simple-cells generate orientation tuned responses by summing inputs from LGN neurons with receptive fields aligned along the preferred orientation. Later studies have confirmed that their scheme is approximately correct (Reid & Alonso, 1995) although additional mechanisms are required for the contrast invariance of the orientation tuning (Finn, Priebe, & Ferster, 2007; Skottun, Bradley, Sclar, Ohzawa, & Freeman, 1987). In similar way, the phase insensitive complex-cells can be generated by summing inputs from appropriate simple-cells (Hubel & Wiesel, 1962).

Neurons with similar orientation preferences form columns on the primary visual cortex and the array of columns spanning 180º has a width of 0.5-1.0 mm in monkeys (Hubel & Wiesel, 1974). In addition to this orientation map, the primary visual cortex contains an ocular dominance map (Hubel & Wiesel, 1974) and a retinotopic map in which neighboring neurons on the cortex have receptive fields at neighboring locations in the visual field (Daniel & Whitteridge, 1961).

A series of seminal papers showed that humans and macaques perceive the visual world similarly (De Valois, Morgan, & Snodderly, 1974; De Valois, Morgan, Polson, Mead, & Hull, 1974) and not surprisingly, the human and macaque visual cortices show many similarities. For example, functional magnetic resonance imaging (fMRI) has demonstrated that ocular dominance and orientation maps are similar in the primary visual cortex of humans and in non-human primates (Yacoub, Harel, & Ugurbil, 2008). Moreover, the human visual cortex contains retinotopic maps and retinotopic mapping has become a standard procedure in visual neuroscience laboratories across the world (e.g. Dumoulin & Wandell, 2008; Henriksson, Karvonen, Salminen-Vaparanta, Railo, & Vanni, 2012; Sereno et al., 1995).

Direct electrical recordings of receptive field properties of visual neurons in humans are rare and limited to patients undergoing surgery (Marg, Adams, & Rutkin, 1968; Yoshor, Bosking, Ghose, & Maunsell, 2007). Thus, most of the evidence concerning similarity of receptive fields in humans and macaques stems from comparisons of human psychophysics and single cell recordings in macaques. Spatial frequency bandwidth of V1 receptive fields is highly similar compared to the bandwidth of spatial frequency adaptation in humans (Blakemore & Campbell, 1969; De Valois, Albrecht, & Thorell, 1982). Moreover, reverse correlation estimates of visual filters underlying orientation, stereo and motion processing in humans show striking similarities to single neuron receptive fields in macaques (Neri & Levi, 2006). The receptive fields of V1 simple cells (Jones & Palmer, 1987) and the filters underlying contrast detection in humans (Kurki, Hyvärinen, & Laurinen, 2006) resemble two-dimensional Gabor functions i.e. Gaussians multiplied by sinusoid. Interestingly, such filters produce maximally sparse responses to natural images (Hyvärinen & Hoyer, 2001; Olshausen & Field, 1996).

The primary visual cortex is certainly not the only cortical region involved in vision as approximately 27% of the human cortex processes predominantly visual information (Van Essen, 2003). Primary visual cortex resides at the bottom of a hierarchy of visual areas (Felleman & Van Essen, 1991) and the other regions are jointly referred as extra-striate cortex (Maunsell & Newsome, 1987). In the secondary visual cortex (V2) of macaques the receptive fields are larger and neurons prefer lower spatial frequencies than in V1 (Foster, Gaska, Nagler, & Pollen, 1985). Similarly in humans, fMRI estimates of population receptive field sizes increase (Dumoulin & Wandell, 2008) and preferred spatial frequency decreases (Henriksson, Nurminen, Hyvärinen, & Vanni, 2008) in cortical areas progressively further from the primary visual cortex. Neurons in the extra-striate visual cortices may have highly complex receptive fields and for example the inferior temporal cortex of both humans and macaques shows selectivity for real world categories such as animate versus inanimate objects (Kriegeskorte et al., 2008). Moreover, selectivity for pattern motion in neurons of the macaque middle temporal area arises from selective pooling of V1 inputs (e.g. Rust, Mante, Simoncelli, & Movshon, 2006) and the angle selective receptive fields in V2 (Ito & Komatsu, 2004) can be formed similarly.

Visual areas connect with reciprocal feedforward-feedback loops in which feedforward connections drive action potentials and feedback connections modulate activity in the recipient region (Felleman & Van Essen, 1991), although recent evidence suggests that feedback may drive the responses at least in rodents (De Pasquale & Sherman, 2011). While functional role of the feedback pathway is not fully understood, it may aid in rapid integration of local signals and global context represented at different levels of the visual system (Bullier, 2001).

1.2 Contextual modulation

A large body of research has shown that processing of visual stimuli in the early visual system depends strongly on the spatial surroundings of the stimuli. Spatial surrounds inhibit photoreceptor responses (Verweij, Hornstein, & Schnapf, 2003) and stimuli that do not elicit response from the retinal ganglion cells may nevertheless reduce firing rates evoked by stimuli inside the classical receptive field (Solomon, Lee, & Sun, 2006). Such reductions are typically termed suppression and in the case that contextual stimuli

increase neural responses the effects are termed facilitation. Spatial context suppresses the firing rates of neurons also in the lateral geniculate nucleus of macaque monkeys (Solomon, White, & Martin, 2002). The contextual effects are typically described as arising from extra-classical receptive field (ECRF) (e.g. Solomon et al., 2002).

In addition to sub-cortical structures, interactions between stimuli inside and outside the classical receptive field are well documented for the early visual cortices of macaque monkeys (Maffei & Fiorentini, 1976; Shushruth, Ichida, Levitt, & Angelucci, 2009; Tanaka et al., 1986). The strongest interactions arise when the center and surround stimuli have the same spatiotemporal frequency (Webb, Dhruv, Solomon, Tailby, & Lennie, 2005) and orientation (Cavanaugh, Bair, & Movshon, 2002b) and nearby stimuli typically interact more strongly than distant ones (Levitt & Lund, 2002). Stimulation of the ECRF typically reduces the response to the stimulus presented in the classical receptive field, but it may also sometimes increase the spike-rates (Ichida, Schwabe, Bressloff, & Angelucci, 2007).

Center-surround interactions in human perception and in the primary visual cortex of monkeys show striking qualitative similarities and researchers sometimes treat the two phenomena in parallel (e.g. Meese, Summers, Holmes, & Wallis, 2007). Humans perceive the contrast of a texture patch as reduced when the patch is embedded in a similar surrounding (Chubb, Sperling, & Solomon, 1989; Ejima & Takahashi, 1985). As in single cells, strength of such center-surround interactions decrease as the spatial frequency (Chubb, et al., 1989) and orientation (Cannon & Fullenkamp, 1991; Solomon, Sperling, & Chubb, 1993) difference between the center and surround increases. Suppression strength increases with surround contrast (Olzak & Laurinen, 1999; Snowden & Hammett, 1998) and facilitation is sometimes observed when the surround is of lower contrast than the center (Xing & Heeger, 2001). Moreover, the strongest center-surround interactions are observed across short distances and increasing the distance weakens the interactions (Cannon & Fullenkamp, 1991, 1996).

Spatial context affects the blood oxygen level dependent (BOLD) responses in the early visual cortices of humans (Dumoulin & Hess, 2006). As in psychophysical and single cell studies, the most often observed effect is suppression (Kastner et al., 2001; Williams, Singh, & Smith, 2003), but also response facilitation sometimes emerges (Tajima et al., 2010). The contextual interactions are tuned for orientation (Pihlaja,

Henriksson, James, & Vanni, 2008; Schumacher & Olman, 2010) and spatial frequency (Pihlaja et al., 2008) difference between the center and surround stimuli. Interestingly, spatial context produces highly similar effects on contrast response functions in humans regardless of whether the estimates were obtained with fMRI or psychophysics (Zenger-Landolt & Heeger, 2003).

Interactions between spatially distant contrast stimuli have been mostly studied using the contrast detection paradigm in humans (e.g. Chan, Battista, & McKendrick, 2012; Chen & Tyler, 2001, 2002, 2008; Kurki et al., 2006; Polat & Sagi, 1994; Solomon, Watson, & Morgan, 1999; Williams & Hess, 1998). Polat and Sagi (1993) showed in their classical demonstrations that the detection threshold of a Gabor-stimulus decreases when it is concurrently displayed with flanking Gabors. The effect is tuned for the orientation difference between the target and the flankers, scales with spatial frequency and persists up to ~10 cycle separation between the target and flanks (Polat & Sagi, 1993). Similarly, a surrounding grating can increase the detection threshold of an embedded Gabor and such suppression can be observed up to 8 cycle distance (Petrov & McKee, 2006; Saarela & Herzog, 2008).

Spatial envelopes of the classical and extra-classical receptive fields have often been studied by varying the size of a grating stimulus centered on the neuron's CRF (e.g. Sceniak, Ringach, Hawken, & Shapley, 1999). These measurements typically yield spike rate versus area functions or area summation functions in which the responses first increase to a peak and then decrease until a plateau is reached. Based on such measurements the spatial structure of the receptive field has been modeled as a central excitatory Gaussian mechanism surrounded by an antagonistic, inhibitory Gaussian mechanism (Cavanaugh, Bair, & Movshon, 2002a; Sceniak, Hawken, & Shapley, 2001). These mechanisms should not be confused with the inhibitory and excitatory sub-regions of the classical receptive field. Following the idea that inhibition normalizes contrast responses in the primary visual cortex (Carandini, Heeger, & Movshon, 1997; Heeger, 1992) the surround mechanisms is thought to act through divisive inhibition (Cavanaugh et al., 2002a), although some authors have considered also subtractive inhibition (Sceniak et al., 2001). Similarly in human vision, the changes in thresholds produced by superimposing a mask upon the target (Foley, 1994; Meese, 2004; Meese & Baker, 2013) and contextual suppression of both thresholds and apparent contrast

(Cannon & Fullenkamp, 1996; Meese, Challinor, Summers, & Baker, 2009; Snowden & Hammett, 1998; Solomon, et al., 1993; Xing & Heeger, 2001) have been modeled as divisive inhibition. Divisive inhibition has also been used in computerized edge detection algorithms (Grigorescu, Petkov, & Westenberg, 2003).

Given the similarity between the experimental results and modeling efforts concerning contextual modulation in single cells and in human vision, it seems striking that the idea of two antagonistic Gaussians has not been, to my best knowledge, considered as a candidate spatial structure for the mechanisms underlying contextual modulation in human cortical vision. Moreover, inhibitory surrounds in V1 neurons most likely involve multiple components with different spatial range (Angelucci et al., 2002) and tuning properties (Webb et al., 2005), which may suggest that contextual interactions are tuned differently depending on distance. This thesis aims to find out how well the two antagonistic Gaussians models fare in modeling contextual interactions in human vision and whether contextual interactions show different properties depending on distance.

2. Aims of the study

Study I

The aim of the first study was to quantitatively characterize the spatial structure of the mechanisms underlying contextual modulation in human vision and to examine whether the antagonistic Gaussians models provide an acceptable description of the structure.

Study II

The aim of the second study was to scrutinize the assumption of the two antagonistic Gaussians models that strength of contextual interactions depends on visual field size of the involved stimuli instead of size of their cortical representations.

Study III

The aim of the third study was to characterize contrast dependencies in long-range spatial interactions in human vision.

Study IV

The aim of the fourth study was to characterize orientation tuning of short- and long-range interactions in human vision and macaque V1 cells and thereby shed light on the orientation specificities of the underlying circuitries.

3. General methods

3.1 Psychophysics

Psychophysics is a tradition and collection of methods for quantitative investigation of the relationship between psychological sensations and physical stimuli. In this thesis psychophysics was used for measuring the effects of spatial context on contrast thresholds and apparent contrast. Contrast threshold is the stimulus contrast with which an observer reports target presence with a pre-specified accuracy and apparent contrast is the contrast with which the observer cannot discriminate the contrasts of the test and comparison stimulus. The threshold depends both on the standard deviation and mean response of the mechanism encoding the target (Green & Swets, 1988) and apparent contrast depends only on the mean.

This thesis exploited the method of constant stimuli introduced by Fechner in 1860 (Gescheider, 1985) and staircase method (Cornsweet, 1962). The method of constant stimuli samples the performance of the observer along the entire psychometric function. The psychometric function is estimated by presenting pre-specified target levels multiple times to the observer and plotting the performance of the observer against the target level. The method of constant stimuli is instrumental in research questions which require the entire psychometric function, but unfortunately, the method is time consuming.

Staircase method quickly locates a single point on the psychometric function by adapting to the responses of the observer (adaptive methods reviewed in Treutwein, 1995). Let me illustrate the staircase method with a hypothetical contrast detection experiment. In the first trial the target is clearly visible and every time the observer indicates target presence its contrast is decreased. When the observer indicates target absence its contrast begins to increase and after the observer again indicates target presence the target contrast starts to decrease again. Fixed number of such reversals is measured and mean of the reversal contrasts is taken as the threshold estimate. Different points on the psychometric function can be targeted by requiring different number of responses for the staircase reversals (Levitt, 1971).

In the above described single staircase method the observers may keep track on the progress of the staircase and thus manipulate the measurement (Cornsweet, 1962).

Double-staircase procedure involves two independently progressing staircases, which reduces the possibility that the observer wittingly influences the measurement (Cornsweet, 1962). All the main experiments in this thesis involved double-staircase or the method of constant stimuli.

Psychophysical equipment

In all of the psychophysical experiments the monitor was a calibrated 22 inches Mitsubishi Diamond Pro 2070 CRT with 800 x 600 pixels (39.0 x 29.2 cm) resolution. The stimuli were created and their timing was controlled with Matlab^{TM} (Natick, MA, USA) and displayed with Cambridge Research System's (Kent, UK) VisaGe graphics card providing 14-bits gray-scale resolution. The viewing distance was always fixed with a chin rest and the measurement room was painted black. The monitor was the only light source during the experiments except for the study II, in which dim background light was on.

3.2 Functional magnetic resonance imaging

Principles of magnetic resonance imaging

Magnetic resonance imaging (MRI) of the brain is based on nuclear magnetic resonance of hydrogen nuclei. In magnetic field the hydrogen nuclei precess at a frequency, which is proportional to the magnetic field strength and hydrogen's gyromagnetic constant. The nuclei can absorb and radiate energy at this Larmor frequency. When subject enters the strong magnetic field of the MRI scanner, small excess of the hydrogen spins align parallel (low-energy state) and the rest anti-parallel (high-energy state) to the magnetic field. Upon delivery of an excitatory pulse some of the spins absorb the energy and switch to high-energy state. As the spins relax back to the low-energy state the longitudal component of the magnetic field increases and structural brain imaging is based on tissue specific differences in the time constant (T_1) of this longitudal relaxation. The excitatory pulse produces also a transverse component to the magnetic field, which relaxes with a time constant T_2 or T_2^* when the magnetic field inhomogeneities are accounted for. Temporal differences in T_2^* time constant constitute the basis for functional magnetic resonance imaging (fMRI). Principles of MRI are reviewed in a book by Huettel, Song and McCarthy (2004).

BOLD signal and its neuronal basis

Local increases in BOLD signal result from the large and delayed influx of oxygenated blood, which follow increased neuronal activity (Logothetis & Wandell, 2004). The oversupply of oxygenated blood forms the basis for BOLD contrast, but the functional role of this excess oxygen supply is not fully understood (Attwell et al., 2010). The oxygenated hemoglobin increases the homogeneity of the magnetic field and correspondingly the time constant T_2^* and BOLD signals (see above).

Studies of human visual cortex have shown that amplitude of the BOLD signal follows neuronal firing rates when simple visual or auditory stimuli are used (Boynton, Demb, Glover, & Heeger, 1999; Mukamel et al., 2005; Rees, Friston, & Koch, 2000). However, studies on the rat cerebellum indicate that spikes are neither necessary nor sufficient for the induction of blood flow changes (Caesar, Thomsen, & Lauritzen, 2003; Thomsen, Offenhauser, & Lauritzen, 2004). Instead, the current literature associates BOLD signals with local field potentials (Goense & Logothetis, 2008; Logothetis, Pauls, Augath, Trinath, & Oeltermann, 2001), which reflect inputs and local processing at a given brain site (Logothetis, 2003) and it is now known that neurotransmitters and astrocytes contribute to the regulation of cerebral blood-flow (Attwell et al., 2010).

Spatial specificity of fMRI

Spatial resolution of an imaging system can be described with its point-spread function. In this thesis majority of the fMRI data was collected using the spin-echo EPI sequence because it provides sharper point-spread than the more conventional the gradient-echo EPI (Parkes et al., 2005). In fMRI the point-spread arises from technical and physiological factors. The technical point-spread is negligible in the frequency-encoded and slice directions (Liang & Lauterburg, 2000) and in the phase-encoded direction the half-width at half-maximum of the point-spread is approximately 0.65 mm in spin-echo EPI (Jesmanowicz, Bandettini, & Hyde, 1998). Similarity of physiological point-spread of fMRI and point-spread of voltage-sensitive dye (VSD) imaging suggests that purely vascular spreading contributes little to the point-spread of fMRI. Expressed as the distance in which the signal amplitude decreases to 1/e of the maximum, the point-

spread in primary visual cortex is 2.1 mm in VSD imaging (Grinvald, Lieke, Frostig, & Hildesheim, 1994) and 2.0 mm in spin-echo EPI (Parkes et al., 2005). These values are in good correspondence with the 2.3 mm length of horizontal connections in the primary visual cortex (Angelucci et al., 2002) and it has been suggested that the horizontal connections form the limiting factor of spatial resolution in fMRI (Engel, Glover, & Wandell, 1997).

Retinotopic mapping

Borders of the early retinotopic visual cortical areas were mapped using standard 60-region (Vanni, Henriksson, & James, 2005) and 24-region multifocal (Henriksson et al., 2012) and phase-encoded (Sereno et al., 1995) procedures. Retinotopic data was collected using gradient-echo EPI.

Surface reconstruction

The human cortex is highly convoluted and therefore merely by overlaying functional and structural volumes it is difficult to identify the visual areas in which a given visual stimulus evoked activity. To facilitate sampling from the desired functional visual areas the evoked activations are often projected to reconstructed and unfolded cortical surface. In this thesis the reconstruction and unfolding were done either with Brain à la Carte Matlab-toolbox (Warnking et al., 2002) (Study I) or the Freesurfer package (Dale, Fischl, & Sereno, 1999; Fischl, Sereno, & Dale, 1999) (Study II). The structural volumes underlying the reconstructions had 1 mm x 1 mm x 1 mm resolution.

3.3 Single cell recordings

The single cell recordings in study IV were conducted by the laboratory of Professor Angelucci in the University of Utah, USA. The animals were anesthetized with sufentanil citrate, paralyzed with vecuronium bromide and artificially respirated using a mixture of O_2 and N_2O. The recordings were made with epoxylite-coated tungsten microelectrodes. Signals were conventionally amplified, filtered between 0.4 kHz-5 kHz and spikes were sampled at 22 kHz. Details of the recording procedure have been previously described (Shushruth et al., 2009) and the procedures conformed to the guidelines of the University of Utah Institutional Animal Care and Use Committee.

4. Specific studies

4.1 Study I: Area summation of luminance contrast in the human visual system

The purpose of the first study was to investigate and quantify the spatial structure of the mechanisms that underlie contextual modulation in humans. Previous studies of contextual modulation in human cortex have focused on the modulation strength (Dumoulin & Hess, 2006; Williams, et al., 2003; Zenger-Landolt & Heeger, 2003), but spatial structure of the modulatory mechanisms has not been described for human V1 and V2. In single cell studies the spatial structure of the modulatory mechanisms has been quantified by measuring area summation functions (Angelucci et al., 2002; Cavanaugh et al., 2002a; Sceniak et al., 1999). These functions have been measured psychophysically in humans (Saarela & Herzog, 2008; Yu & Levi, 1997) but unfortunately, quantified area summation data does not exist for humans. This study expands the current understanding of the spatial structure of the modulatory mechanisms by reporting quantified area summation functions for human perception and visual cortices V1 and V2.

4.1.1 Methods

Perceptual area summation functions were estimated by measuring the detection threshold of a Gabor target (SD 0.125º) on grating pedestals of different diameters (0.5, 2, 4, 8 and 24º) (Yu & Levi, 1997) (Figure 1a). This is an extension of the Westheimer (1967) paradigm to the contrast domain. Visual parameters of the pedestal and target were the same, except for size and contrast. The threshold versus pedestal diameter functions were fitted with difference-of-integrals of Gaussians functions and three quantities were extracted from the fits. Summation field size is the pedestal diameter at which the function peaks and surround field size is the diameter at which threshold is 5% above the threshold at the largest pedestal. Suppression index is the difference

between thresholds at the function peak and largest pedestal size normalized by the threshold at the peak.

Area summation functions for human visual cortices V1 and V2 were measured using General Electric Signa EXCITE 3.0 T MRI (General Electric Medical Systems, Milwaukee, WI, USA) scanner. Sixteen 2.5 mm thick slices were imaged using 64 x 64 imaging matrix with 160 mm field of view. The repetition time was 1800 ms, and the echo-time was 70 ms. Spatial layout of the stimuli was identical with the psychophysical experiment, but the stimuli were displayed in 10.8 sec blocks. BOLD signal change was quantified from those single V1 and V2 voxels, which showed the largest t-values in independent localizer runs.

4.1.2 Results

Perceptual area summation

As in single cells in the primary visual cortex (Sceniak et al., 1999), the area summation functions first increased to a peak and then decreased until a plateau was reached (Figure 1b). Averaged over the subjects (N=4), the summation field size was 2.1 ± 0.30º (mean ± 95% CI) and the surround field size was 6.2 ± 2.5º. The mean suppression index was 0.34 ± 0.08. In single cells of the macaque primary visual cortex (Cavanaugh et al., 2002a), the mean summation field size, surround field size and suppression index are, 2.7 ± 0.14º, 4.5 ± 0.22º and 0.32 ± 0.02, respectively.

Area summation in human V1 and V2

Area summation functions for human visual cortices V1 and V2 were qualitatively similar with the perceptual functions (Figure 1c). However, suppression was stronger and summation and surround field sizes were larger than in the psychophysical data. In V1, the summation field size was 3.2 ± 1.3º (mean ± 95% CI), surround field size was 15 ± 2.3º and suppression index was 0.87 ± 0.23. In V2, the summation field size was 5.6 ± 6.0º, surround field size was 15 ± 6.4º and the suppression index was 0.83 ± 0.68.

Which factors may underlie the pronounced quantitative differences in area summation between psychophysics and fMRI? Perhaps the simplest difference between fMRI and psychophysics is the inherently different resolution of the methods. In this study the voxel covered approximately 2º x 2º region of the visual field and therefore

the receptive fields of the sampled neuronal population were also similarly scattered on the visual field. In psychophysical tasks the situation is different, however, because at least in direction discrimination humans rely mainly on the most informative neurons (Jazayeri & Movshon, 2006, 2007). In the current contrast discrimination task these neurons are likely to have receptive field centers on the center of the Gabor target where the largest change between pedestal and pedestal + target takes place.

A modeling approach was taken in order to understand the impact of the visual field coverage of a voxel on area summation in fMRI. The model consisted of stereotypical model neurons in which the receptive field was described with a two-dimensional variant of the difference-of-integrals of Gaussians model (Sceniak et al., 2001). The visual field locations of the receptive fields were computed with the inverse of Schwartz (1994) formula using parameters that produce the average cortical magnification in human V1 (Duncan & Boynton, 2003). The other model parameters were fixed to produce the mean summation and surround field sizes and suppression index in the psychophysical experiment. As the array of orientation columns spanning 180º has a width of 0.5-1.0 mm (Hubel & Wiesel, 1974) a voxel with typical dimensions most likely contains a uniform distribution of orientation preferences (Haynes & Rees, 2005). Thus, stimulus orientation in the fMRI experiment was necessarily suboptimal for some neurons and the model took this into account. Furthermore, the model accounted for the technical point-spread of spin-echo EPI. There were no free parameters in the model.

The modeled area summation functions were qualitatively similar to those measured in the psychophysical and in the fMRI experiments (Figure 3b). In good harmony with the fMRI data, the modeled summation field size was 3.7º. Thus, the different resolution in fMRI and psychophysics accounts well for the differences in summation field sizes as measured with the two methods. However, the modeled surround field size and suppression index were clearly smaller than the measured values.

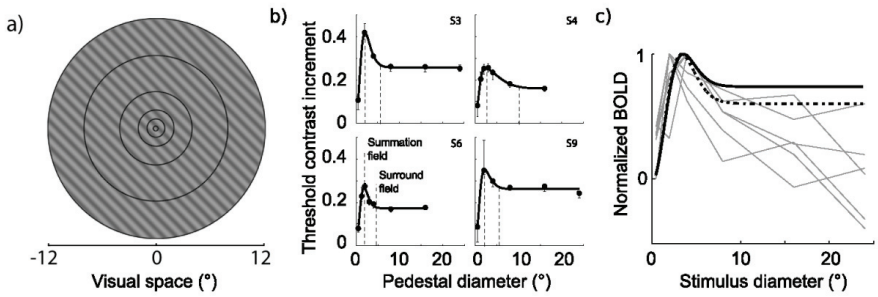

Figure 1 a) Grating pedestals used both in the psychophysical and fMRI experiments. b) Psychophysical area summation functions fitted with the model (smooth curves). Different subjects in different panels. c) Gray lines are the area summation functions for V1 of individual subjects. The dotted curve represents the model including orientation preference in the individual model neurons. Solid curve is the model without orientation tuning.

What sources could underlie the discrepancy of the measured and modeled surround field size and suppression index? The model was based on psychophysics and some of the discrepancy may relate to the different neural underpinnings of BOLD and psychophysics. BOLD signal reflects synaptic activity (Logothetis et al., 2001) whereas discrimination performance relates to the spiking output of small number neurons (Shadlen, Britten, Newsome, & Movshon, 1996). The synaptic responses in turn sometimes exhibit stronger suppression than spike responses (Anderson, Lampl, Gillespie, & Ferster, 2001) possibly leading to stronger suppression in fMRI than in the psychophysics based model.

4.2 Study II: Fovea-periphery axis symmetry of contextual modulation

The purpose of the second study was to investigate whether strength of contextual modulation is determined by visual field size or cortical size of the interacting stimuli. Current models of contextual modulation (Cavanaugh et al., 2002a; Sceniak et al., 2001) posit that visual field size determines modulation strength, but this assumption has not been rigorously tested. Petrov, Popple and McKee (2007) used appropriate stimuli for testing the assumption, but ceiling effects may have compromised their conclusions. To shed light on the determinants of contextual modulation strength, surround modulation was measured with two surrounds which were identical in visual

field size but differed markedly in the size of their cortical representations. Ceiling effects were controlled for.

4.2.1 Methods

Psychophysics

Double-staircase procedure was used for measuring surround suppression of the apparent contrast of a peripherally viewed (6º eccentricity) center grating (diameter 1.8º). The surrounds extended either towards the fovea (inward surround) or periphery (outward surround) from the center and although their visual field sizes were identical, cortical magnification rendered the expected sizes of their cortical representations markedly different (Figure 2). The possibility of ceiling effects was minimized by varying size of the gap separating the center and the surrounds.

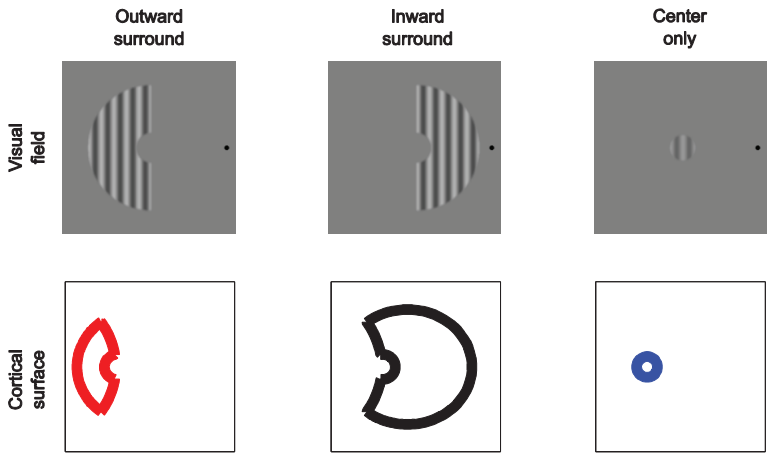

Figure 2 The upper row shows examples of the stimuli used in Study II and the bottom row shows the corresponding cortical representations computed using the Schwartz (1994) formula with parameters producing cortical magnification in human V1.

fMRI

Surround suppression of BOLD signal was measured with Siemens MAGNETOM Skyra 3T MRI (Siemens AB, Erlangen, Germany) scanner using spin-echo EPI. Standard preprocessing steps were implemented with the SPM8 software package (Wellcome trust center for neuroimaging, London, UK). The center diameter (3º) was optimized for fMRI and due to limited scanning time only three gap sizes were used (0.1, 0.6 and 1.8º). Otherwise the stimuli were identical to those used in the psychophysical experiment. The stimuli were displayed in 10.8 sec blocks and BOLD signal was sampled as follows. First, the voxels in which the activity in independent localizer runs crossed the statistical threshold (t-test, FWE correction, $p<0.05$) were projected to the unfolded surface of the primary visual cortex. The analyses were then confined to the single voxel situated nearest to the geometrical center of the projected cluster.

4.2.2 Results

Despite having markedly different sized cortical representations the surrounds produced highly similar reductions in the apparent contrast of the center (Figure 3a). For the inward surround, suppression strength decreased from 24.5 ± 4.2% to 4.7 ± 1.5% (paired t-test $p<0.05$) with increasing the gap size from 0.1º to 2.1º. The corresponding decrease for the outward surround was from 18.7 ± 4.2% to 3.5 ± 2.1% (paired t-test $p<0.05$).

In harmony with the psychophysical data, the two surrounds suppressed BOLD response to the center with highly similar magnitudes (Figure 3b). For the inward surround the mean (N=7) suppression strength decreased from 29.9 ± 9.0 % to 3.1 ± 5.0 % as the gap size was increased. For the outward surround, the corresponding decrease was from 25.6 ± 9.0 % to -0.7 ± 3.8 %. Differences between the two surround types were not statistically significant (paired t-test, $p>0.05$).

The model developed in the first study was used for predicting surround suppression of apparent contrast and BOLD responses. Parameters of the model were fixed in a separate psychophysical area summation experiment. To model the psychophysical surround suppression merely one model cell with receptive field centered on the

stimulus was used. For fMRI, 441 model cells distributed on the visual field coverage of the modeled voxel was used. The suppression strength of the fMRI model was scaled by 2.71, because the first study of this thesis showed that suppression strengths differ by this factor between V1 cells and fMRI.

The modeled functions were similar compared to the functions measured with fMRI. This corroborates the assumption that interaction strength depends on the visual field sizes of the interacting stimuli. Moreover, the modeling results indicate that antagonistic Gaussians models provide good approximation of contextual modulation in the human visual system also in situations for which they were not originally developed for. The model was not a good description of the psychophysical data in subject S4 who was an outlier also in the area summation measurements constraining the model parameters.

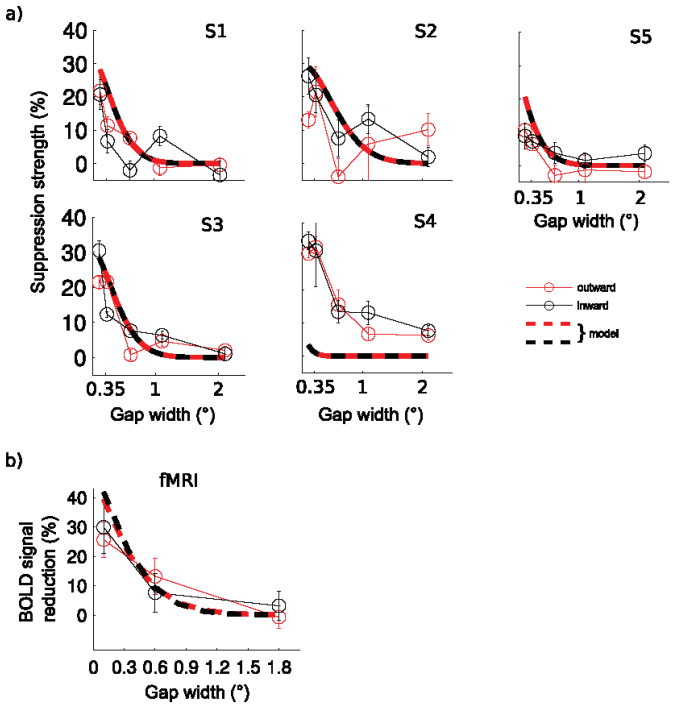

Figure 3 a) Psychophysical surround suppression versus gap width functions for inward and outward surround conditions in five subjects. The smooth curves represent the modeled suppression. b) BOLD signal reduction versus gap width averaged over the subjects. The smooth curves represent the modeled results.

4.3 Study III: Very long-range spatial interactions in human contrast perception

The purpose of the third study was to further test how well the antagonistic Gaussians models describe contextual modulation in the human visual system. Single cell studies have shown that these models break down at relatively low center contrast and large distance between center and surround stimulus (Ichida et al., 2007; Schwabe, Ichida, Shushruth, Mangapathy, & Angelucci, 2010). Interactions between distant stimuli have been mainly studied at the detection threshold in humans (Petrov & McKee, 2006; Polat & Sagi, 1993), but it is difficult to relate these studies to neural responses. This is because some of the threshold effects may arise from reduction in uncertainty of the target location (Petrov, Verghese, & McKee, 2006; Williams & Hess, 1998). This study provides the first detailed suprathreshold measurements concerning the contrast dependency of center-surround interactions at large distances.

4.3.1 Methods

The method of constant stimuli was used for measuring the apparent contrast of a center grating (diameter 0.8º, 2.4 cycles) in the presence of 1º (3 cycles) wide surrounds (Figure 4a). In the first experiment, the width of the gap between center and surround was varied between 0.1º (0.3 cycles) and 6.6º (19.8 cycles). In the second experiment constant gap width (6.6º) and three center contrasts (5, 15 and 75%) were used and the surround-to-center contrast ratio was varied from 0 to 3.

4.3.2 Results

As in previous studies (Cannon & Fullenkamp, 1991), suppression strength decreased as size of the gap was increased (Figure 4b). Interestingly, facilitation was found when the gap size was larger than 3º. This is in contrast with predictions of the standard antagonistic Gaussian models (Cavanaugh et al., 2002a; Sceniak et al., 2001) and previous suggestions that facilitation of apparent contrast arises only from surround regions that lie near the center (Xing & Heeger, 2001).

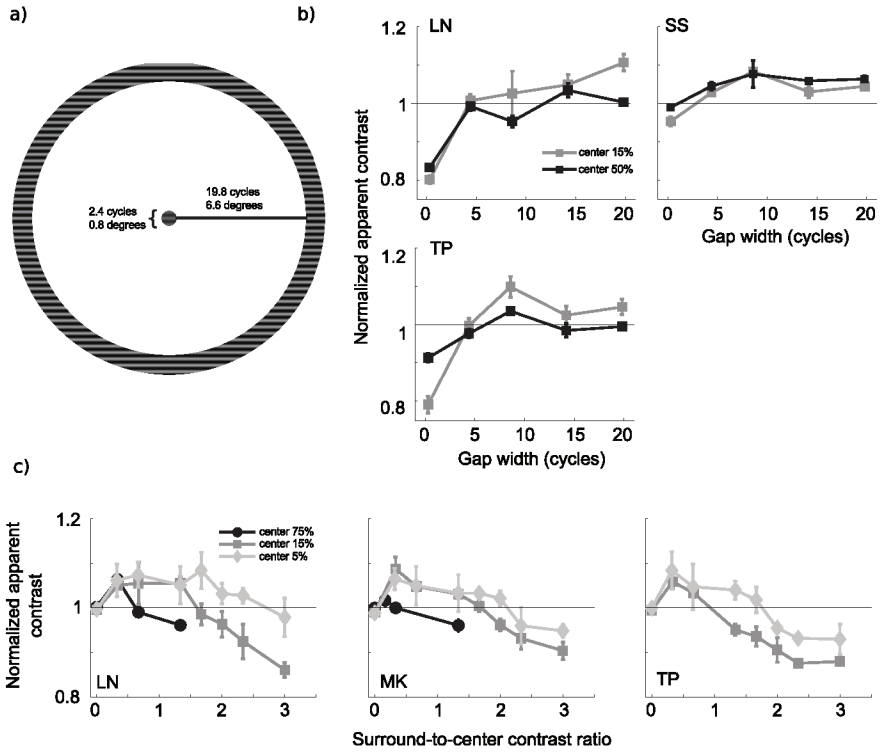

Figure 4 a) The most distant surround type used in the experiments. b) Apparent contrast as a function of the gap size. Values below the horizontal line indicate suppression and the values above it indicate facilitation. Different subjects in different panels. c) Apparent contrast as a function of surround contrast at different center contrasts. X-axis values larger than one indicate that surround contrast was higher than center contrast. Horizontal line as in b).

The second experiment of this study focused on contrast dependency of the long-range facilitation and suppression. Surround facilitated the apparent contrast of the center when the surround contrast was low and at higher surround contrasts suppression was observed (Figure 4c). Strength of facilitation could even exceed strength of suppression, whereas short-range facilitation has been consistently found to be weaker than suppression (Snowden & Hammett, 1998; Xing & Heeger, 2001).

4.4 Study IV. Orientation tuning of near and far surround modulation

The purpose of the fourth study was to further investigate potential differences between long- and short-range contextual modulations. Physiological studies suggest that the

highly divergent (Angelucci et al., 2002) and fast conducting (Girard, Hupe, & Bullier, 2001) feedback connections subserve long-range interactions, whereas both the horizontal and feedback connections contribute to short-range interactions (Angelucci & Bressloff, 2006). In line with the orientation tuned short-range interactions (Cannon & Fullenkamp, 1991; Cavanaugh et al., 2002b; Levitt & Lund, 1997) the horizontal connections link cells with similar orientation preferences (Bosking, Zhang, Schofield, & Fitzpatrick, 1997; Malach, Amir, Harel, & Grinvald, 1993). However, while some studies have reported orientation specificity in the feedback projection from the extra-striate areas to the primary visual cortex (Stettler, Das, Bennett, & Gilbert, 2002), others have not found such orientation specificity (Shmuel et al., 2005). Previous studies of orientation tuning of contextual modulation have not isolated short and long-range effects and thus their potential differences are unknown. Here, orientation tuning of short and long-range contextual modulation was measured for both human perception and single V1 cells.

4.4.1 Methods

Apparent contrast and spike responses to a center grating were measured in the presence of two surround types. The near surround was placed within the reach of V1 horizontal connections and the far surround mostly beyond their reach. Size of the far surround was selected so that the near and far surrounds would produce approximately the same suppression strengths. The center-surround orientation difference was varied from 0º to 90º.

4.4.2 Results

Increasing the center-surround orientation difference from 0º to 90º markedly decreased strength of the near surround suppression for both the human observers and V1 cells (Figure 5a). However, the center-surround orientation difference had only modest effect on strength of the far surround suppression (Figure 5b). The averaged suppression tuning curves for V1 cells and human observers were clearly overlapping (Figure 5a,b).

Figure 5c shows the orientation tuning, indexed with circular variance (Cavanaugh et al., 2002b), of far versus near surround suppression for all of the observers and cells.

Clearly, most of the points fall below the diagonal, which indicates that near surround suppression was more orientation tuned than the far surround suppression.

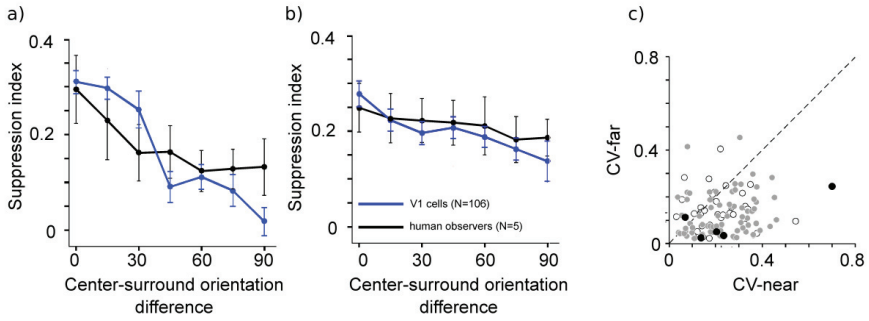

Figure 5 a) Surround suppression as a function of the center-surround orientation difference in V1 cells and in human perception. Surround was near the center. Larger values indicate stronger suppression. b) The same as a) but the surround was far from the center. c) Orientation tuning of the suppression indexed with circular variance. Symbols below the diagonal indicate cases in which the effects from the near surround were more orientation tuned than the effects from the far surround. Black dots mark human observers, gray dots mark cells with suppression and open dots mark the cells without suppression.

5. Discussion

5.1 Spatial structure of the modulatory mechanisms

The area summation functions reported in this thesis were similar to those frequently observed in single cell studies (e.g. Angelucci et al., 2002). The qualitative agreement suggests that contextual modulation arises from mechanisms with similar spatial structure in humans and macaques. In particular, the functions were accurately modeled by assuming that the contextual effects arise from spatially overlapping and antagonistic mechanisms with Gaussian shaped spatial profiles. This is a standard model of contextual effects in visual neurophysiology (Angelucci et al., 2002; Cavanaugh et al., 2002a; Sceniak et al., 2001) and thus this thesis bridges investigations at the level of single cells, macroscopic cortical activation and perception.

The non-monotonic area summation functions were clearly different compared to earlier studies in humans, which have consistently reported monotonically decreasing threshold versus area functions (Foley, Varadharajan, Koh, & Farias, 2007; Howell & Hess, 1978; Meese & Summers, 2012; Rovamo, Luntinen, & Näsänen, 1993). However,

observers may use monotonically increasing number of cells for the task as the target size increases and if so, then the threshold versus area functions would be monotonically decreasing (Green & Swets, 1988). This is hardly possible in this thesis as the area summation functions were measured using fixed sized target. In addition, it is possible that the near threshold contrasts that were used in the previous studies abolished surround inhibition as it weakens at low stimulus contrasts (Sceniak et al., 1999). Thus, the apparent discrepancy between area summation in this thesis and in the earlier studies probably arises from the different tasks and stimuli that were used. The task involved in the earlier studies involves pooling over multiple mechanisms, whereas the task used in this thesis most likely reveals properties of a single mechanisms.

The two antagonistic Gaussians models assume that it is indifferent whether a stimulus appears in a context extending towards the fovea or periphery (e.g. Cavanaugh et al., 2002a). However, size of the cortical representation of a stimulus depends on eccentricity (Duncan & Boynton, 2003; Horton & Hoyt, 1991) and cortical size may in fact determine strength of the interactions. The second study of this thesis showed, in accordance with the antagonistic Gaussians models, that visual field size of the contextual stimuli indeed determines strength of the interactions. This is an important result for at least two reasons. Firstly, the study tested and verified an underlying assumption of the models and thus justified their use as a starting point for developing more detailed models of contextual modulation in human vision. Secondly, the study showed that the effects of spatial context upon a stimulus at fixed eccentricity are insensitive to fovea-periphery anisotropies. This is an important result as increasing number of studies have attempted to link contextual modulation to natural image statistics (Coen-Cagli, Dayan, & Schwartz, 2012; Schwartz, Sejnowski, & Dayan, 2009; Schwartz & Simoncelli, 2001) and fovea-periphery distinction is incommensurable with natural image statistics.

Previous psychophysical studies have suggested that the mechanism underlying suppression is spatially wide spread whereas facilitation is spatially restricted (Xing & Heeger, 2001). Similarly, the antagonistic Gaussians models predict both facilitation and suppression across small distances whereas at large distances they predict either suppression or no effects at all (Cavanaugh et al., 2002a; Sceniak et al., 2001). The third study of this thesis clearly showed that these predictions are incorrect. In accordance

with the predictions, suppression strength decreased as the distance between the center and surround stimulus was increased. However, in the current foveal measurements suppression turned into facilitation as the distance exceeded approximately three degrees. Thus, both this thesis and previous single cell studies (Ichida et al., 2007) clearly demonstrate that the earlier scheme in which suppression arises from a much larger region of the visual field than facilitation (Cavanaugh et al., 2002a; Sceniak et al., 2001; Xing & Heeger, 2001) is inaccurate. Instead, contextual modulation is better accounted by assuming that suppression and facilitation arise from similar region of the visual field.

It is rather well known that contextual interactions show clear orientation tuning both in human perception (Cannon & Fullenkamp, 1991; Petrov, Carandini, & McKee, 2005; Polat & Sagi, 1993; Solomon, et al., 1993) and in single cells of monkeys and cats (Cavanaugh et al., 2002b; DeAngelis, Freeman, & Ohzawa, 1994; Levitt & Lund, 1997; Sengpiel, Sen, & Blakemore, 1997; Sillito, Grieve, Jones, Cudeiro, & Davis, 1995; Walker, Ohzawa, & Freeman, 1999). In one previous study the orientation tuning of short and long-range interactions was compared (Hashemi-Nezhad & Lyon, 2012), but unfortunately in that study short- and long-range interactions were of different magnitude which may have caused the difference in tuning. Thus, in the fourth study of this thesis the orientation tuning was compared in situations producing approximately the same interaction strengths. Both in human vision and in single cells in the macaque primary visual cortex, short-range interactions were more narrowly tuned than the long-range interactions. Interestingly, this pattern resembles natural contour statistics, in which nearby edges of the same contour have high probability of being co-oriented whereas the more distant edges assume wider distribution of orientations (Geisler, Perry, Super, & Gallogly, 2001). Thus, by reducing the spike rates to the most frequently occurring natural contours contextual interactions may reduce the high energy costs related to maintaining the ion gradients that are necessary for generating the spikes (Attwell & Laughlin, 2001). In fact, reducing energy consumption is one of the suggested functional roles of contextual modulation (Vanni & Rosenström, 2011).

The resemblance between natural contour statistics and orientation tuning of contextual modulation stimulates the question whether contextual interactions may aid in integrating local orientation signals into extended contours (Field, Hayes, & Hess,

1993). Contextual suppression of apparent contrast shows some similarities with contour integration in that both are tuned for spatial frequency (Chubb et al., 1989; Dakin & Hess, 1998) and are insensitive for spatial phase (Field, Hayes, & Hess, 2000; Xing & Heeger, 2001). While contour integration shows interocular transfer (Huang, Hess, & Dakin, 2006), interocular transfer of surround suppression of apparent contrast was reported in one study (Meese & Hess, 2004) whereas another study did not find interocular transfer (Chubb et al., 1989). However, the apparent contrast of a Gabor remains approximately constant between displays containing and not containing a contour (Hess, Dakin, & Field, 1998) and thus it seems that mechanisms other than surround suppression are required for contour detection.

5.2 Circuitry and mechanisms

The approximately 2 mm monosynaptic reach of V1 horizontal connections (Angelucci et al., 2002) is clearly below the spatial range of contextual interactions found in this thesis and in previous psychophysical and single cell studies (Cannon & Fullenkamp, 1991; Ichida et al., 2007). The range and rapid onset of the interactions in macaque V1 (Bair, Cavanaugh, & Movshon, 2003) and in human perception (Kilpeläinen, Donner, & Laurinen, 2007) seems better compatible with the fast conducting (Girard et al., 2001) and spatially extensive (Angelucci & Bullier, 2003) feedforward-feedback projection. However, the second study of this thesis showed that contextual interactions were symmetric with respect to the fovea-periphery axis of the visual field. This is a puzzle because while feedback projection shows the spatiotemporal characteristics required for contextual interactions, it is asymmetric in the fovea-periphery axis in the visual field (Angelucci et al., 2002). The horizontal connections in turn show fovea-periphery axis symmetry in the visual field (Angelucci et al., 2002), but not the spatial range and speed required for the contextual interactions. The puzzle might be solved if, as previously suggested for monkeys (Schwabe et al., 2010; Schwabe, Obermayer, Angelucci, & Bressloff, 2006), contextual interactions would rely on both the horizontal and feedback projection also in humans.

While it is known that horizontal axons in layers 2-3 of the primary visual cortex connect cells with similar orientation preferences (Bosking et al., 1997; Malach et al., 1993), there is a controversy concerning the orientation specificity of the feedback

projection. The V2 to V1 feedback is orientation unspecific in macaques (Stettler et al., 2002), but specific in owl monkeys (Shmuel et al., 2005). The stimulus design in the fourth study of this thesis assured that mainly the feedback projection conveyed the long-range interactions. Thus, the broad orientation tuning of the long-range effects suggests that feedback projection is less orientation specific than the horizontal projection. However, the short- and long-range effects were equally tuned for orientation in layer 4B, which is in line with the patchy termination of feedback in this layer (Lund, Angelucci, & Bressloff, 2003). Given that the orientation tuning of surround suppression is altered in patients suffering from schizophrenia (Yoon et al., 2009) this thesis may have clinical implications in the future.

Long-range contextual facilitation has often been studied by measuring the detection threshold of a Gabor-target in the presence of flanking Gabors (e.g. Chan et al., 2012; Polat & Sagi, 1993; Wu & Chen, 2010). Facilitation of detection may arise from reduction in location uncertainty of the target (Levi, Klein, & Hariharan, 2002; Petrov, et al., 2006; Williams & Hess, 1998), but because uncertainty reduction is a threshold phenomenon (Williams & Hess, 1998) the suprathreshold facilitation found in this thesis cannot arise from such mechanism. Thus, something else must be at play. It is well known that low contrast pedestals facilitate detection (Campbell & Kulikowski, 1966; Kilpeläinen, Nurminen, & Donner, 2012) and Solomon et al. (1999) and Kurki et al. (2006) suggested that contextual stimuli act as low contrast pedestals for the target and thus facilitate detection. However, the pedestal explanation predicts that increasing surround contrast either increases facilitation or produces no effects at all whereas the fourth study of this thesis showed that facilitation turns into suppression as the surround contrast increases. While all the above mechanisms may contribute to facilitation at threshold the facilitation in this thesis is better compatible with explanations based on changes in gain (e.g. Chen & Tyler, 2008)

5.3 Comparisons across methods

Earlier studies have reported relatively good correspondence in strength of contextual modulation in the primary visual cortex and perception in humans (Schumacher &

Olman, 2010; Wade & Rowland, 2010; Zenger-Landolt & Heeger, 2003) and this thesis provides the first spatial characterizations of the relationship. The first study of this thesis introduced a novel method for comparing the spatial aspects of contextual modulation as measured with psychophysics, single cell recordings and fMRI. The hallmark of the method was the use of tissue specific spin-echo EPI, to analyze just one voxel and to model its visual field coverage. While the measured and modeled summation field sizes agreed well, surround sizes and suppression strengths were clearly different in the first study. Moreover, the shapes of the measured and modeled functions were somewhat different as the modeled responses saturated and the measured responses did not. However, the second study took differences in suppression strength between fMRI and V1 cells into account, which brought the spatial properties of contextual modulation in psychophysics and fMRI into agreement. This demonstration is important as it ties, for the first time, spatial properties of contextual modulation in human vision to V1 physiology. The demonstration is not trivial, as for example Press et al. (2001) reported entirely flat V1 area summation for dartboard patters, where stereotypical non-monotonic area summation functions were clearly expected.

It is necessarily complicated to compare functions obtained with single cell recordings in anesthetized macaques and with psychophysics in humans. Some of the difficulty relates to the fact that anesthetics may profoundly alter sensory responses (Haider, Hausser, & Carandini, 2013; Lamme, Zipser, & Spekreijse, 1998), which in turn may obscure the comparisons. Moreover, assigning psychophysical performance to a certain brain region is necessarily a best guess and the different sized neural populations targeted by the methods do not lessen the hardship. Appreciating these difficulties, however, comparisons between single cell responses and human psychophysics formed an essential ingredient of this thesis.

The opening study of this thesis compared psychophysical area summation functions to single cell data extracted from recordings reported in two studies by Cavanaugh, Bair and Movshon (2002a,b). The similarity of the obtained functions clearly suggests that underlying mechanisms are similar. However, the psychophysical area summation functions were collected using the detection on a pedestal paradigm, which reflects changes in both the mean and variance of the neural population underlying the performance in the task. While the use of detection task was a necessity in measuring

the area summation functions, it might not be optimal for comparisons to single cell studies which typically report mean spike rates (but see Geisler & Albrecht, 1997). Previous studies have directly compared contextual effects in single V1 neurons and human psychophysics (Kapadia, Ito, Gilbert, & Westheimer, 1995; Li, Thier, & Wehrhahn, 2000). While these studies were highly informative and reported positive correlation between V1 neurons and human psychophysics they suffered from the drawback of comparing mean spike rates to thresholds and in these studies it was also possible that the contextual stimuli encroached to the excitatory center of the recorded neurons. The closing study of this thesis overcame such limitations and showed a good correspondence between orientation tuning of the contextual effects in human vision and V1 cells.

6. Conclusions

This thesis provided spatial characterization of the mechanisms that underlie contextual interactions in the early visual system. It was shown (Studies I and II) that two antagonistic Gaussians provide a fairly good first approximation of the structure in humans. Study III provided evidence that stimulus contrast may change antagonism to synergy even at very long distances. Study IV added orientation dimension and demonstrated that interactions across short distances show narrower orientation specificity than interactions across long distances. The thesis provided estimates concerning spatial structure of the modulatory mechanisms that were in reasonable agreement not only across the different measurement methods, but also across species.

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