Electrophysiological Events Related to Top-Down Contrast Sensitivity Control

by

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Abstract

Stimulus-driven changes in the gain of sensory neurons are well-documented, but relatively little is known about whether analogous gain-control can also be effected in a top-down manner. A recent psychophysical study demonstrated that sensitivity to luminance contrast can be modulated by a priori knowledge (de la Rosa et al., in press). In the present study, event-related potentials were used to resolve the stages of information processing that facilitate such knowledge-driven adjustments. Groupwise independent component analysis identified two robust spatiotemporal patterns of endogenous brain activity that captured experimental effects. The first pattern was associated with obligatory processing of contextual information, while the second pattern was associated with selective initiation of contrast gain adjustment. These data suggest that knowledge-driven contrast gain control is mediated by multiple independent electrogenic sources.

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Table of Contents

INTRODUCTION	1
Neural Manifestations of Contrast Sensitivity	2
Temporal Properties	5
Attention	6
Top-Down Control: de la Rosa, Gordon & Schneider	7
Top-Down vs. Bottom-Up: Neural Manifestations	8
MATERIALS AND METHODS	13
Experiment I	13
ERP Recording and pre-processing	15
Experiment II	17
Data Analysis	17
RESULTS	20
Experiment I	20
Experiment II	21
PLS Results	21
DISCUSSION	30
Behavior	30
Event-Related Potentials	30
REFERENCES	38

List of Figures

Figure 1.	Control flow of Experiment I.	14
Figure 2.	Cap configuration for the 76-channel ActiveTwo cap.	16
Figure 3.	Mean percent accuracy for low-contrast trials for the three conditions in Experiment I.	14
Figure 4.	Task-specific grand average ERP amplitudes at four representative electrodes.	14
Figure 5.	Amplitude distributions for the Baseline and Valid-Cue conditions and their difference.	24
Figure 6.	Task-related components.	25
Figure 7.	Average amplitudes for cue- and task-specific conditions at one representative electrode.	26
Figure 8.	Cue-type components common to all conditions.	27
Figure 9.	Cue-type components unique to the Valid-Cue condition.	28

Introduction

Successful object perception partly depends on the ability of the observer to parse a visual scene into objects. Objects can often be separated from their background and from each other as a result of subtle luminance and color contrasts along edges and mutual borders. These properties of the environment are therefore significant sources of information and sensitivity to contrasts is an important feature of the visual system. Please note that this literature review and research proposal specifically concern luminance contrast and not color contrast. Unless stated otherwise, the term ‘contrast’ refers to luminance contrast.

Regardless of their specialized function or their station in the hierarchy of visual processing, most cortical visual neurons are sensitive to the level of contrast within their receptive field (RF) and their response profile varies somewhat predictably as a monotonic, increasing function of contrast (Albrecht & Hamilton, 1982). Response rates are accelerated and the response function is characterized by an expansive nonlinearity over low levels of contrast. As contrast increases, the response function becomes approximately linear. At high levels of contrast, the response rates saturate such that the response function has a second nonlinear region. Namely, the response function becomes compressed and asymptotes to some maximal response level.

Despite considerable heterogeneity across individual neurons, the contrast-response function (CRF) generally maintains this sigmoidal shape (Albrecht & Hamilton, 1982) and can be fitted with the Naka-Rushton function (Naka & Rushton, 1966):

$$f(x) = r_{\max} x^n / (x^n + x_{50}^n)$$

where x represents contrast, $r_{\max}$ represents the firing rate at which the response saturates and x_{50} represents the semisaturation constant: the point at which 50% of the maximal response is attained. The slope of the function, which corresponds to the rate of change of the response, is represented by the exponent n . As will shortly become clear, it is useful to parameterize experimental contrast-response data in this way because it allows for

most commonly observed phenomena to be conveniently described in terms of simple parameter manipulations.

Contrast increments over the intermediate segment of the CRF elicit the greatest changes in the response and this segment is often termed the ‘dynamic range’. Therefore, the dynamic range of a given neuron is the range of contrasts over which the response is informative, but this range is considerably narrower than the range of contrasts likely to be encountered in the environment (Albrecht & Hamilton, 1982; Frazor & Geisler, 2006). To maintain sensitivity, gain is controlled and continuously adjusted in response to fluctuations of local contrast (Ohzawa, Sclar & Freeman, 1982; 1985).

The precise means of gain-control is still subject to debate, but data from most studies have converged on two possibilities, both of which involve multiplicative mechanisms. The first is that the contrast necessary to elicit a given response is multiplied, thus changing the *contrast-gain*. This serves to center the CRF on the average ambient level of contrast (e.g. Gardner et al., 2005; Ohzawa et al., 1982), effectively shifting the dynamic range. Graphically, this corresponds to a lateral shift of the CRF, which can be modeled by changing the value of x_{50} . The second is that *response-gain* is adjusted through a multiplication of the response by a constant factor proportional to the average ambient contrast (e.g. Geisler & Albrecht, 1992). This is equivalent to scaling the CRF and can be modeled by manipulating the $r_{\max}$ term of the Naka-Rushton function.

Neural Manifestations of Contrast Sensitivity

Thus far, the precise definition of ‘response’ has been left intentionally ambiguous and little attempt has been made to describe the nature of the processing units or their location. As previously noted, contrast sensitivity and gain-control are near-ubiquitous properties of visual neurons and typical CRFs can be acquired using a variety of recording techniques. Using single-cell recordings, they have been observed in cat striate cortex (Albrecht & Hamilton, 1982; Ohzawa et al., 1982; 1985; Sclar, Ohzawa & Freeman, 1982), monkey primary visual cortex (Albrecht & Hamilton, 1982; Albrecht et al., 2002; Sclar, Maunsell & Lonnie, 1990), area V4 (Cheng et al., 1994) and middle temporal area

(MT; Cheng et al., 1994; Kohn & Movshon, 2003; Sclar et al., 1990). In these studies, the ‘response’ is the firing rate of an individual cell.

Neuroimaging techniques such as functional magnetic resonance imaging (fMRI) have also revealed contrast sensitivity and gain-control in the human visual cortex, including areas V1, V2, V3, V4 and MT (Avidan et al., 2001; Boynton et al., 1999; Gardner et al., 2005; Heeger et al., 2000; Tootell et al., 1995; 1997). In these studies, the ‘response’ variable is the hemodynamic or blood-oxygen-level dependent (BOLD) signal that depends on the activity of many neurons.

In addition, visually evoked potentials (VEPs) measured using electroencephalography (EEG) over the occipital lobe are also sensitive to stimulus contrast and standard CRFs can be computed using VEP amplitude as an index of the response (Spekreijse, Van der Tweel & Zuidema, 1973). These cortical responses are also subject to contrast sensitivity control mechanisms (Porciatti et al., 2000). Interestingly, VEP latency also depends on contrast, with phase advances resulting from increasing stimulus contrast (Porticatti et al., 2000; Spekreijse et al., 1973).

Moreover, the neurophysiological measures provided by various methods are remarkably consistent with psychophysical contrast detection thresholds. For example, detection thresholds can be reliably predicted from single-cell responses (Geisler & Albrect, 1997), VEPs (Cannon, 1983) and BOLD responses (Boynton et al., 1999). This suggests a relatively direct link between neural activity and perceived contrast.

Despite their substantial dependence on the level of local contrast and their response saturation at higher contrasts, neurons in the visual cortices typically maintain their functional selectivity when contrast is varied. For example, orientation (Sclar & Freeman, 1982) and direction selectivity (Sclar et al., 1990; Tootell et al., 1995; 1997) remain invariant with stimulus contrast. However, in terms of the absolute sensitivity to contrasts, the precise shape of the CRF and temporal response profiles there is still considerable heterogeneity across individual neurons (e.g. Albrecht & Hamilton, 1982; Albrecht et al., 2002). Distinct regions of the visual cortices may also differ in this respect. For example, Avidan et al. (2001) reported that contrast sensitivity gradually

declines along the ventral stream, from high sensitivity in area V1 to low sensitivity in higher order occipito-temporal areas, such as the lateral occipital complex (LOC). Likewise, disparate areas such as V1 (Boynton et al., 1999) and MT (Tootell et al., 1995) tend to have markedly different dynamic ranges and saturation points, while CRFs computed from responses in ventral visual areas such as V2v, V3v and V4v are occasionally non-monotonic (Boynton et al., 1999).

These phenomena are not purely cortical, but are also present in earlier stages of visual processing. For example, Sclar et al. (1990) showed that cells in the lateral geniculate nucleus (LGN) are also sensitive to contrasts and display a typical sigmoidal CRF. In addition, several authors have posited that contrast-gain control mechanisms may even operate at the retinal level (Baccus & Meister, 2002), most likely mediated by retinal ganglion cells (Shapley & Victor, 1979; 1981). However, one caveat that should be noted is that increasing contrast is insufficient to cause response saturation or latency shifts of retinal evoked potentials (Morrone et al., 1994), both of which are typical findings for cortical VEPs.

Though it appears that contrast sensitivity varies somewhat systematically along the visual pathway, the particular pattern is still unclear. As previously mentioned, Avidan et al. (2001) showed that contrast sensitivity declines along the ventral stream from area V1 to the LOC. However, Sclar et al. (1990) showed that neurons that form the geniculocortical pathway become increasingly sensitive to contrasts as one moves from the LGN to area MT. These results are not necessarily contradictory. The two studies examined different stages in the hierarchy of visual processing. In addition, they most likely examined different functional streams as well, with Avidan et al. (2001) focusing on the ventral and Sclar et al. (1990) on the dorsal stream. By virtue of their distinct functional characteristics it is possible that visual processing in the two streams differentially depends on image contrast and neurons from these streams differentially adapt their responses to changes in local contrast. Finally, the two studies used different types of stimuli. Avidan et al. (2001) only reported a stronger contrast invariance trend for images of faces than for images of objects.

Temporal Properties

Thus far, neural contrast sensitivity has been discussed with respect to anatomical loci and static gain-control mechanisms. To understand the full functional range of contrast-sensitive visual processing, one must also take into account the temporal scale on which such processing takes place. This is because the local contrast over the RF of a given neuron can change as rapidly as every 200-300 ms, or roughly the length of time the eyes spend fixated on one location before the next saccade is initiated. Since the correlation between local contrasts falls rapidly with spatial distance, both the rate and the magnitude of the change of local contrast will be considerable, suggesting a need for extremely rapid contrast sensitivity control mechanisms (Frazor & Geisler, 2005).

Not surprisingly, many studies have revealed a class of contrast sensitivity control mechanisms that operate rapidly enough to compensate for these changes in local contrast (Albrecht et al., 2002; Geisler, Albrecht & Crane, 2007; Sclar & Freeman, 1982), broadly termed ‘contrast normalization’. Other studies have revealed another, slower form of gain-control that operates over several seconds (Ohzawa et al., 1982; 1985) and is reminiscent of simple adaptation (Albrecht et al., 2002).

Contrast sensitivity and gain-control strongly depend on stimulus contrast and traditionally have been assumed to operate in ‘bottom-up’ fashion. Slow adaptation may be such a stimulus-driven, ‘bottom-up’ mechanism (Albrecht et al., 2002). On the other hand, it seems plausible that contrast normalization – a type of contrast sensitivity control that needs to create rapid adjustments in response to changes in local contrast – would benefit from advanced knowledge about the level of contrast likely to be encountered, such as when one is scanning a familiar scene. Since eye movements can be controlled by central mechanisms, this sort of information may be readily available. Therefore, it may be the case that contrast-sensitive processes in the visual system additionally interact with ‘top-down’ processes.

Attention

The interaction between top-down processing and contrast-sensitive visual perception may take effect through attention and there is a large body of evidence to suggest that stimulus contrast and attention are closely linked. For example, contrast is a stimulus dimension that can be selected for by attention during visual search like other stimulus features such as colour, shape or orientation (Pashler, Dobkins & Huang, 2004).

Interestingly, it appears that unique attentional resources are allocated for contrasts defined by luminance, separate from those allocated for contrasts defined by colour (Morrone, Denti & Spinelli, 2004).

More importantly, apparent contrast can be enhanced by attention. In psychophysical studies, covert shifts of attention (also termed ‘transient’ attention) tend to decrease the increment stimulus threshold (the smallest contrast increment that can be reliably detected) for all baseline contrasts (Carrasco, Ling & Read, 2004; Huang & Dobkins, 2005; Ling & Carrasco, 2007), though it has also been suggested that this enhanced contrast sensitivity may be due to sensory interactions instead (Schneider, 2006). Likewise, studies using single-cell recordings have demonstrated that contrast-dependent neuronal responses can also be enhanced by attention (Reynolds, Pasternak & Desimone, 2000; Martinez-Trujillo & Treue, 2002), regardless of whether attention is shifted exogenously or endogenously (Ling & Carrasco, 2006).

Though there is consensus that attention serves to increase contrast sensitivity, there is also much disagreement as to how neuronal processing is adjusted to generate this effect. Some have suggested that attention acts by modulating contrast gain, because attentional modulation varies nonlinearly with stimulus contrast (Martinez-Trujillo & Treue, 2002) and has the greatest effect when the stimulus contrast is in the dynamic range of the neuron (Reynolds et al., 2000). It has also been proposed that attention amplifies both contrast and response gain (Huang & Dobkins, 2005). Ling and Carrasco (2006) partially agree with this view, but have argued that the fashion in which attention is engaged is the determining factor, such that transient attention modulates both contrast gain and response gain, but sustained attention modulates contrast gain only. Finally, in a

recent fMRI study Buracas and Boynton (2007) found that attentional modulation of the BOLD response was independent of stimulus contrast. They proposed a new, ‘additive’ model in which attention serves to add a constant to the response regardless of stimulus contrast. Graphically, this is equivalent to a vertical shift of the CRF. Whatever the specific mechanism may be, it is clear that attention interacts with contrast sensitivity control processes and some authors have even suggested the two may be mediated by common neural hardware (Martinez-Trujillo & Treue, 2002).

However, most attentional modulation effects cited thus far cannot be said to have true “top-down” character, because they either strongly depend on the local contrast or on transient shifts of visuospatial attention. One unique finding was that contrast sensitivity can be modulated through endogenous shifts of attention (Ling & Carrasco, 2006). This suggests that adjustments in contrast sensitivity may also be subject to central cognitive control.

Top-Down Control: de la Rosa, Gordon & Schneider

The study by de la Rosa, Gordon and Schneider (in press) was designed to test the possibility that contrast sensitivity may be controlled in a central, purely top-down manner, driven entirely by contextual knowledge and independent of attention. They reasoned that a priori knowledge of the prevailing levels of contrasts likely to be encountered in the immediate future should be capable of normalizing contrast sensitivity. The purpose of this cognitive control mechanism would be to match contrast sensitivity to impending changes in ambient contrast, such that contrast information about the upcoming visual scene is maximized.

This notion was tested using a cued absolute identification task. Participants were asked to identify a series of cued gratings by their contrast. Four gratings in the stimulus set had relatively low contrast and were difficult to identify, while a fifth grating had extremely high contrast and was relatively easy to identify. In one condition (Baseline) only the four low-contrast gratings were presented. In another condition (Invalid-Cue) the high-contrast grating was also presented, but was unpredictable. In the third condition

(Valid-Cue) the high-contrast grating was predicted by a cue. The identity of the specific low-contrast grating was unpredictable in all conditions.

Participants' contrast sensitivity (indexed by their ability to correctly identify low-contrast gratings) could be assessed while systematically manipulating the predictability of a high-contrast grating. The addition of an occasional high-contrast grating to the stimulus set adversely affected identification accuracy for low-contrast gratings relative to the condition in which only the low-contrast gratings are presented. However, when the high-contrast grating was made predictable by way of the cue, there was no such accuracy cost.

The authors hypothesized that top-down control over contrast sensitivity specifically serves to protect contrast-sensitive circuits from overload. It has previously been demonstrated that higher cognitive systems exert top-down control over auditory gain to protect against intensity overload (Parker, Schneider & Murphy, 2002). De la Rosa et al. (in press) argued that a comparable control system could exist in vision, possibly to limit discharge in contrast-sensitive neurons in order to prevent excessive cortical excitability (Porciatti et al., 2000).

In a second experiment, participants were presented with a stimulus set of four high-contrast gratings in one condition and an additional unpredictable low-contrast grating in another condition. This time, there was no difference in identification accuracy for the high-contrast gratings between the two conditions. The results were consistent with the notion that contrast sensitivity was set to protect against sensory overload, because identification accuracy only suffered from the addition of a high contrast stimulus but was unaffected by the addition of a low contrast stimulus.

Top-Down vs. Bottom-Up: Neural Manifestations

Several authors have already posited that the brain proactively makes predictions about future events in the visual environment by adjusting cortical communication in a downstream manner (e.g. Kveraga, Ghuman & Bar, 2007). The study by de la Rosa et al. is singular because it shows for the first time that there exists a higher, top-down control

mechanism that is capable of tuning contrast-gain. It does so independently from attention and from bottom-up stimulus features such as contrast. However, bottom-up and top-down processing are relative concepts. From a behavioral perspective, one can infer that a task was performed in a bottom-up or top-down fashion depending on whether performance was constrained by information inherent entirely in the stimuli or by the subjects' knowledge and/or expectations.

From a neural perspective, the operational definitions of bottom-up and top-down processing are considerably different and much less distinct. This is because it is exceedingly difficult to define what constitutes the 'top' of a processing hierarchy that includes as many lateral and feedback connections as the visual system does (Barlow, 1997). For example, neurophysiological studies indicate that stimulus-driven adjustments in primary visual cortex are mediated by intracortical short-range reciprocal connections (Das & Gilbert, 1999) and by thalamic feedback modulation (Sillito et al., 1994). In addition, one could argue that much of the 'knowledge' utilized by the visual system is in fact derived from the structure of the input signal and by feedback (Barlow, 1997).

Though it may be difficult to define the source of 'top-down' processes, it is not impossible. Bar et al. (2006) showed that top-down predictions used in visual object recognition were associated with early activity in the orbitofrontal cortex (OFC). It is possible that top-down contrast sensitivity control may originate from a similar region. Top-down contextual associations used to facilitate object recognition are typically considered to be primarily semantic in nature (e.g. Kveraga et al., 2007). However, recognition most likely depends on contrast-*invariant* representations of objects and in the ventral pathway there is a noted trend towards increasing contrast invariance in higher-level 'object areas', such as the LOC (Avidan et al., 2001). Hence, contrast sensitivity may be an equally important facet of contextual knowledge, in the sense that top-down control mechanisms could be used to ensure that object representations in high-level areas remain invariant to changes in contrast.

This raises an equally important question. Namely, where in the visual processing stream is top-down control of sensory gain implemented? By virtue of its bidirectional

connections with both the frontal and visual cortices, the thalamus appears to be a likely locus (Skinner & Yingling, 1977). The thalamus is well-suited for a regulatory role in sensory transmission because of its position as a primary sensory relay as well as the feedback loop nature of thalamocortical projections (Birbaumer et al., 1990; Brunia & Van Boxtel, 2001; Elbert & Rockstroh, 1987; Skinner & Yingling, 1976, 1977).

The objective of the current study was to place the behavioral effect reported by de la Rosa and colleagues in a psychophysiological context. Event-related potentials (ERPs) were used as a means of formulating a coherent framework in which to simultaneously study the interplay of a cognitive construct (top-down control) with a physiological one (contrast sensitivity).

Scalp-recorded ERPs are voltage fluctuations in the electroencephalogram (EEG) that occur as a result of electrical fields generated by the summation of postsynaptic potentials in cortical patches. ERPs that are related to some event can be isolated from the EEG by averaging trials that are time-locked to that event. The isolated ERPs typically consist of a series of positive and negative voltage peaks or “components” that signify the precise latency and rough anatomical locus of evoked brain activity. The ERP technique was well-suited to address the goals of the current study for two reasons. One, ERPs allow the quantification of changes in electrophysiological activity in response to psychological manipulations. In addition, the precise physical and psychological parameters that affect most major ERP components are already well-known. Two, the temporal resolution of the ERP technique can be used to resolve different stages of information processing in the brain. This is a particularly desirable attribute because the temporal scale over which the effect occurs is unknown.

To elucidate top-down modulation in a psychophysiological sense, we sought to identify a difference in endogenous ERP components that were related to the informative value of the cue. Namely, when only low-contrast stimuli are possible (Baseline) and when the high-contrast stimulus is unpredictable (Invalid-Cue), the ERP waveforms time-locked to the cue should be different compared with the situation in which the high-contrast grating is predictable (Valid-Cue). This is because in the Baseline and Invalid-

Cue conditions contrast sensitivity is presumably pre-adjusted (to high and low levels, respectively) as soon as one is informed about the contents and predictability of the stimulus set. Thus, there should be no trial-to-trial, post-cue adjustment of contrast sensitivity. If such adjustments do happen, there is no a priori reason to suspect they will be time-locked to the cue. Conversely, in the Valid-Cue condition participants should be able to adjust their sensitivity in response to each cue, leading to markedly different spatiotemporal patterns of cortical activity.

Moreover, the expression of this effect was expected to include topographic regions outside of the visual cortex, reflecting the contribution of some central mechanism involved in cognitive processing of the cue. If any adjustments take place, they would not be driven by information inherent solely in the stimulus but also by contextual knowledge of stimulus meaning (de la Rosa et al., in press). Therefore, some cue-related activity should be observed outside of visual areas. Since contrast invariance is critical to successful object recognition, it may be the case that rapid top-down control of contrast sensitivity and top-down predictions that facilitate object perception originate from a common prefrontal source, such as the OFC (Bar et al., 2006).

The ERP components affected are likely to be endogenous. That is, they are unlikely to include early components that reflect simple sensory responses such as P1 and instead should include later components related to cognitive processing, such as N2 and P3. Given the cue-target, S_1 - S_2 nature of the behavioral task, it is likely that some form of frontal slow wave will be observed during the inter-stimulus interval, such as the Contingent Negative Variation (CNV, Walter et al., 1964). In addition, negative slow waves are concomitant with activity in cortico-thalamic feedback loops (Skinner & Yingling, 1976, 1977). If top-down control of sensory gain is effected at the level of the thalamus, cortical slow waves may be modulated in task-dependent fashion.

In an effort to efficiently capture both the spatial and temporal dynamics associated with top-down cue-driven effects, we used independent component analysis (ICA). This blind source separation technique allowed us to express the electrode data using a smaller number of components: robust spatiotemporal patterns that are maximally

spatially invariant and temporally independent. Since independence is maximized in a temporal sense, this technique was ideally suited to studying how experimental effects are expressed across distinct stages of information processing.

An alternative view of the data reported by De la Rosa et al. (in press) posits that participants do not use the informative cue predicting high-contrast gratings to tune sensory gain, but rather to somehow avoid the certain occurrence of the high-contrast grating in those trials, perhaps by blinking, by moving their eyes or by “defocusing” attention. In this view, gain is at a constant level in all conditions but sensitivity is adversely affected by an occasional high-contrast grating that saturates cortical responses. Therefore, high-contrast stimuli cause a performance decrement in the Invalid-Cue condition, but have no effect in the Valid-Cue condition where they can be avoided. Experiment II was designed to behaviorally test this hypothesis by forcing participants to make a perceptual judgment about high-contrast stimuli as well as low-contrast stimuli.

Materials and Methods

Experiment I

Participants

Fifteen naïve, healthy young adults (mean age 23.6 years) participated in the ERP experiment (Experiment I). Five participants took part in Experiment II. All participants were right-handed and reported normal or corrected-to-normal vision. Each individual provided written informed consent in accordance with the joint Baycrest Centre-University of Toronto Research Ethics Committee and was reimbursed for their participation.

Stimuli and task

The target stimuli were a set of three vertical sinusoidal gratings generated in MATLAB (Mathworks, Inc.), using the Psychophysics Toolbox extension (Brainard, 1997). The gratings were identical in all physical characteristics (5 x 5° visual angle, spatial frequency 4 cpd and phase equal to 0) save for contrast, such that two gratings had relatively low contrast (19% and 26%) while the third had a high contrast (100%). This manipulation served not only to create a high-low separation within the set, but also to increase difficulty of correctly identifying low-contrast gratings, as they are more similar to each other than to the high-contrast grating.

Participants were seated in a dimly-lit room at a viewing distance of 60cm from a computer screen while stimuli were presented centrally over a uniform grey background (luminance: 55.16 cd/m²). In each trial participants were exposed to a symbolic cue followed by a grating, presented for 550ms and 500ms respectively and separated by an inter-stimulus interval (ISI) equal to 500ms (Figure 1). The cue could be either a plus sign (“+”) or a letter “H”. The task was to correctly identify the grating by the relative magnitude of its contrast, using a number key on a keyboard. The 19%-, 26%- and 100%-contrast gratings corresponded to keys numbered 1, 2 and 3, respectively. The onset of

the grating was also the start of a response period limited to 2s. Participants were instructed to respond as accurately as possible, even at the cost of slowed reaction time (RT). At the end of the response period participants were shown the correct number of the grating (1, 2 or 3, presented for 500ms), regardless of whether their own response was correct or incorrect in that trial. The inter-trial interval between the offset of the feedback stimulus at the end of one trial and the onset of the cue at the start of the next trial was varied randomly and with equal probability between 800ms and 1200ms to reduce expectancy effects.

Figure 1. Symbolic cues (“+” or “H”) were presented for 550ms and following a constant ISI (500ms) one of three vertical sinusoidal gratings was presented for 500ms. After a 2s response period, correct-answer feedback was presented for 500ms. The inter-trial interval from the offset of the feedback stimulus in one trial and the onset of the cue stimulus in the next was equiprobable from 800-1200ms. All stimuli were presented centrally against a uniform grey background.

Trials were organized into condition-specific blocks that differed in terms of which gratings could possibly be presented as well as the informative value of the cues. In the Baseline (B) condition, only the two low-contrast gratings (1 and 2) could appear on any given trial. In the Valid-Cue (VC) and Invalid-Cue (IC) conditions all three gratings (1-3) could appear. Each grating was presented 33 times in each block and each condition consisted of two blocks. Thus, Baseline blocks consisted of 66 trials each, while Valid- and Invalid-Cue blocks consisted of 99 trials each.

In both the Baseline and Invalid-Cue conditions, the “H” cue was randomly assigned to precede 8 of the 33 presentations of each grating, while the “+” cue was assigned to precede the other 25 presentations. In other words, the ‘H’ cue appeared on 25% of the trials and the ‘+’ cue appeared on 75% of the trials. This random and equiprobable assignment ensured that the cues were uninformative and could not be used to predict the stimulus contrast. In the Valid-Cue condition the “H” cue was always assigned to trials in which the high-contrast grating (stimulus 3) would be presented and the “+” cue was always assigned to trials in which the low-contrast gratings (stimuli 1 and 2) would be presented. Therefore, the cues were informative in each trial because they could be used to predict whether the contrast of the ensuing stimulus would be high or low.

Participants were verbally advised about the task and cue validity prior to each block of trials. Each participant completed 66 Baseline trials as a practice block (discarded from the analysis) as well as two consecutive blocks of each condition. All participants initially completed two blocks of the Baseline condition, while the order of the subsequent condition-specific block pairs was counterbalanced across participants. Thus, each participant completed a total of 66 practice trials and 528 experimental trials.

ERP Recording and pre-processing

Electroencephalogram (EEG) activity was continuously digitized and amplified with a band-pass of 0-100 Hz and sampled at a rate of 512 Hz from 76 scalp locations using Ag/Ag-Cl-tipped electrodes attached to a custom cap according to the standard 10/20

system (Figure 2). Recordings were made using the Active-Two system (BioSemi, Amsterdam, Netherlands) which does not require impedance measurements or an online reference. All offline processing and artifact correction was performed using EEGLAB software (Delorme and Makeig, 2004). Continuous recordings were downsampled to 256 Hz, average-referenced, high-pass filtered at 0.1 Hz and notch-filtered at 60 Hz. Data were then epoched into 1950ms segments with a 200ms baseline prior to cue onset. Artifacts were identified and corrected using Independent Component Analysis (ICA).

Figure 2. Cap configuration for the 76-channel ActiveTwo cap. Channels are positioned and labeled according to the 10/20 system. Positions are displayed in spherical coordinates in degrees by azimuth (from Cz, positive is right hemisphere, negative is left hemisphere) and latitude (from T7 from left hemisphere and from T8 for right hemisphere, positive is anti-clockwise, negative is clockwise).

Both correct- and incorrect-response trials were included in all analyses. For those analyses specifically concerned with evoked potentials to the grating, data were epoched into 1100ms segments with a 200ms baseline prior to grating onset.

Experiment II

This purely behavioral control experiment was essentially identical to the procedure described above with one important change. All high-contrast trials (in the Valid- and Invalid-Cue) conditions were no longer comprised of only 100%-contrast gratings, but were equally divided between 79%- and 100%-contrast gratings (stimuli 3 and 4). The task was identical to the earlier task in all other aspects. In other words, in the Valid-Cue condition the “H” cue still accurately predicted the onset of a high-contrast stimulus, but this time the cue could not be solely used to identify the grating. Participants had to pay attention to the contrast of the grating in order to identify it.

Data Analysis

Groupwise ICA

Data from all participants were concatenated and the optimal number of dimensions representing the data was determined using the Bayesian Information Criterion (BIC; Hansen et al., 2001). A model with nine dimensions yielded the maximum BIC probability. Concatenated data were subjected to principal components analysis (PCA) for dimensionality reduction, followed by ICA (Kovacevic & McIntosh, 2007). The term “group” ICA is denotes that the procedure is effectively performed across all subjects and conditions simultaneously. Subject- and condition-specific component single trial activations were calculated by multiplying the corresponding time series in electrode space by the ICA mixing matrix. The resulting single trial component activations were averaged across trials to yield condition-specific component waveforms for each participant.

Spatiotemporal Partial Least Squares (ST-PLS)

ST-PLS was performed in both electrode (Lobaugh et al., 2001) and component space (Kovacevic & McIntosh, 2007). Signal amplitude data matrices were constructed such that all participants within conditions were represented in the rows and all time points within channels in the columns. Two variants of ST-PLS analysis were performed. In the first, data matrices were mean-centered columnwise relative to condition-specific grand averages. Consequently, this type of analysis is termed “mean-centered” ST-PLS. A singular value decomposition (SVD) performed on this input matrix yielded a set of mutually-orthogonal latent variables (LVs) in descending order of magnitude. Each LV corresponded to a particular experimental effect and was comprised of: (1) a singular value, indicating the covariance of the experimental effect with ERP amplitude (2) design saliences, representing the task contrast accounted for by that LV and (3) “electrode” saliences, used to isolate the time points within electrodes/components where the aforementioned task contrast is expressed. The singular value was then used to calculate the proportion of cross-block covariance accounted for by each LV (by taking a ratio of the value over the summed squares of all singular values) and thus provided a measure of the relative magnitude of that experimental effect. As no a priori hypothesis had been set, the SVD extracted the main task effects simply by their magnitude.

In the second, hypothesis-driven type of ST-PLS analysis (also called “contrast” or “non-rotated” ST-PLS) a set of a priori task contrasts was first defined (McIntosh & Lobaugh, 2004). A matrix of contrasts was constructed accordingly for each participant and projected onto the input matrix. The resulting signal amplitude-contrast covariance matrix was then subjected to SVD as before to yield a set of LVs that capture the desired task effects.

The statistical significance of the contrast denoted by each LV was determined by performing permutation tests (with 500 replications) on their singular values. Singular values were permuted by randomly re-ordering rows of the data matrix (i.e. reassigning conditions within participants) and calculating a new set of LVs at each permutation. The proportion of times the permuted singular value exceeded the original singular value was

then used to estimate the probability of observing the latter by chance, which is expressed as a probability. The stability of experimental effects at each time point was estimated by bootstrap resampling with replacement of participants within conditions (200 replications). This allowed standard errors to be computed for all saliences. The ratio of a salience to its bootstrap standard error may therefore be interpreted as an index of its reliability across participants.

Therefore, this type of analysis sought to compute the optimal least-squares fit to part of a covariance matrix. This “part” is the cross-block correlation between sets of exogenous (contrasts defining the experimental design) and dependent (electrode/component signal amplitude) measures. Mean-centering PLS analysis identified data-driven task effects while non-rotated PLS analysis evaluated hypothesis-driven task effects. In both instances, the analysis served to elucidate the spatiotemporal expression of task effects by identifying the data points at which those effects were stable across subjects.

Behavioral PLS

While ST-PLS allows an examination of spatiotemporal patterns in brain data attributable to experimental design, it does not provide any information about how these patterns relate to behavioral measures. An important aspect of the present study was to determine whether any task-dependent patterns of neural activity could be also used to predict task performance. To this end, behavioral PLS (McIntosh & Lobaugh, 2004) was used to identify task differences in brain-behavior correlations, where the behavior of interest was z-score transformed identification accuracy for the two low-contrast gratings. This procedure is similar to ST-PLS described above, except that SVD is performed on a matrix of correlations between ERP time series and accuracy, across participants within task.

Results

Experiment I

Identification accuracy for the high-contrast stimulus was extremely high in both Valid- and Invalid-Cue conditions (>99%) and participants did not report any difficulty in identifying it. Identification accuracy for the low-contrast gratings was subjected to a series of *t*-tests which revealed no significant difference between the Baseline and Valid-Cue conditions $t(15)=0.66, p=0.521$. However, there were significant differences between the Baseline and Invalid-Cue conditions $t(15)=3.40, p=0.004$, as well as between the Valid-Cue and Invalid-Cue conditions $t(15)=3.58, p=0.003$. These data are displayed in Figure 3.

Figure 3. Mean percent accuracy for low-contrast trials for the three conditions in Experiment I. Bars indicate one SE from the mean.

A similar analysis of RTs to low-contrast gratings was undertaken, but failed to find any conditions-specific differences. However, correlation analyses did reveal a significant positive association between RT and accuracy, but only in the Valid-Cue condition ($r=0.775, p=0.001$).

In an effort to determine whether practice effects contributed to any long-range drifts in accuracy, we computed identification accuracy for low-contrast gratings separately for each block and performed a two-way repeated measures analysis of variance (ANOVA) with condition and within-condition block order (1st or 2nd) as within-subject factors. This analysis yielded no significant main effect of block order, nor any interaction between block order and condition. Likewise, to examine whether practice effects contributed any short term benefits to accuracy, we computed accuracy for low-contrast gratings separately for the first and second halves of each experimental block. A two-way ANOVA with condition and block half (1st or 2nd) as within-subject factors also failed to find any significant main effect of block half, nor any interaction between block half and condition.

Experiment II

The identification accuracy for high-contrast gratings was above-chance in both Invalid-Cue (67.4%) and Valid-Cue (72.5%) conditions. The behavioral gain effect for low-contrast gratings was still present. In other words, there was no significant difference in identification accuracy between the Baseline and Valid-Cue conditions $t(5)=1.01$, $p=0.359$. However, there were significant differences between the Baseline and Invalid-Cue conditions $t(5)=3.98$, $p=0.011$, as well as between the Valid-Cue and Invalid-Cue conditions $t(5)=3.37$, $p=0.02$.

PLS Results

Valid-Cue versus Baseline, Invalid Cue in electrode space

Non-rotated ST-PLS analysis was used to test the a priori hypothesis that ERPs following the cue would be different in the Baseline and Invalid-Cue conditions compared with the Valid-Cue condition. The analysis only included trials in which the cue was the “+” symbol to ensure epochs were time-locked to the same physical stimulus. The analyses covering the interval from cue onset to grating onset (1050ms) revealed the experimental effect to be significant by permutation test, $p<0.030$.

Figure 4 shows that this effect was primarily expressed at two distinct topographic regions. It was greatest over bilateral occipital and parietal-occipital electrodes (e.g. CB1/CB2, PO7, P10). The effect materialized 190ms following cue onset and remained stable until approximately 600ms. The stability of the effect was assessed by bootstrap resampling and is denoted by the blue markers. The effect appears to map onto differences in amplitude across the P2-N2-P3 component complex. Specifically, ERP amplitude in the Valid-Cue condition is attenuated relative to Baseline and Invalid-Cue.

A complementary expression of the LV can also be observed at the vertex (FCz/FC1/FC2, Cz/C1/C2, CPz/CP1/CP2) emerging approximately 210ms following cue onset until 600ms. The effect here is polarity-reversed relative to the parietal-occipital channels, such that task differences map onto weaker *negative* amplitude in the Valid-Cue condition compared with the Baseline and Invalid-Cue conditions. In addition, the average waveforms during the stability period are comprised of an initial negative peak at approximately 250ms and a positive peak at 300ms, followed by a negative slow wave resembling the Contingent Negative Variation (CNV) wave. Figure 4 shows average amplitudes for four representative channels, two at the vertex and two at parietal-occipital electrodes.

To confirm that this was the dominant effect in the interval, the same data were also subjected to a mean-centering ST-PLS analysis, which yielded only one significant LV ($p < 0.02$). This LV captured the same main effect of Baseline and Invalid-Cue versus Valid-Cue and represented 64.45% of cross-block covariance. Mean-centering ST-PLS analysis of the same low-contrast trials but over a shorter interval (200ms following cue onset: long enough to include only exogenous ERP components such as P1 and N1) failed to produce a statistically significant LV.

Figure 4. Task-specific grand average ERP amplitudes at four representative electrodes. Top left panel: statistical contrasts testing the difference Baseline/Invalid-Cue and Valid-Cue “+”-cue trials. Top right panel: topographic distribution of bootstrap ratios at time $t = 300\text{ms}$. Bottom panel: graphs depicting grand average amplitudes at FC1 (middle left), C2 (middle right), PO7 (bottom left) and CB2 (bottom right). The blue dots represent time points where the statistical contrast shown in the top left panel is reliable by bootstrap test.

The inclusion of several distinct deflections in this experimental effect suggests that the statistical contrast captured by the LV may be a consequence of task differences across more than one underlying electrogenic process. Indeed, the amplitude distribution of difference waves computed from the Baseline and Valid-Cue conditions appears to be time-dependent, with a posterior-going shift from 250ms to 330ms following cue onset (Fig. 5).

Figure 5. Amplitude distributions for the Baseline (left column) and Valid-Cue (middle column) conditions and for their difference (right column), at 250ms (top row) and 330ms (bottom row) following cue onset. The main distribution of the difference wave shifts towards more posterior electrodes.

Valid-Cue versus Baseline, Invalid Cue in component space

An analogous non-rotated ST-PLS analysis performed in component space revealed the Valid-Cue condition to be significantly different from the others ($p < 0.001$). This effect was primarily expressed in two components: IC 1 and 3 (Fig. 6). IC1 captured an early parietal-occipital expression of effect (210-410ms) while IC3 captured a later, more sustained central-parietal aspect (350ms to grating onset).

Figure 6. Task-related components. Top panel: statistical contrasts testing the difference between Baseline/Invalid-Cue and Valid-Cue conditions for “+”-cue trials only. Middle panel: grand average activations for IC 1. Bottom panel: grand average activations for IC 3. The blue dots represent time points where the statistical contrast shown in the top panel is reliable by bootstrap test.

Cue type (+ versus H) in electrode space

In order to test whether the cue elicited any preparatory activity unique to the Valid-Cue condition, data time-locked to the cue were organized into condition- and cue-specific blocks (across high- and low-contrast trials). Non-rotated ST-PLS analyses were designed to contrast brain responses to the two cues (“+” versus “H”), separately for the Baseline and Invalid-Cue conditions on one hand and for the Valid-Cue condition on the other. In both instances, task differences were significant by permutation test ($p < 0.001$) and most stable over a diffuse array of central (Cz/1/2/3/4) and central-parietal channels (CPz/1/2/3/4). In all conditions the difference manifested as a higher-amplitude P3 wave in the “H”-cue trials with peak latency at approximately 500ms. However, the magnitude of the difference was noticeably greater in the Valid-Cue condition.

Figure 7. Average amplitudes for cue- and task-specific conditions at one representative electrode (Pz). Top row: statistical contrasts testing the difference between “+” and “H” cue trials, separately for Baseline/Invalid-Cue (left) and Valid-Cue (right) conditions. The graphs depict grand average amplitudes in the Baseline and Invalid-Cue conditions (left) and Valid-Cue condition (right). The blue dots represent time points where the statistical contrast shown in the top panel is reliable by bootstrap test.

To confirm that cue-specific effects in the Valid-Cue condition could be differentiated from analogous effects in the other two conditions, difference waves between “+” and “H” cues were computed separately for each condition. As suspected, mean-centering ST-PLS analysis revealed a single significant LV ($p < 0.004$) that captured a contrast between the difference waveforms in the Valid-Cue condition versus the difference waveforms in the other two conditions. This LV had a spatiotemporal expression virtually identical to LV1 described above and accounted for 59.18% of cross-block covariance.

Cue type (+ versus H) in component space

In an attempt to isolate any spatiotemporal patterns related to cue-type but unique to the Valid-Cue condition, an analogous non-rotated analysis was performed in component space that separately tested the effects of cue type (“H” versus “+”) in the Baseline/Invalid-Cue and Valid-Cue conditions. In both cases, the contrasts were highly significant ($p < 0.001$) and were expressed over some common components (IC 6 and IC 9,

Fig. 8), though the contrast in the Valid-Cue condition was additionally captured by another pair of components (IC 1 and IC 3, Fig. 10).

Figure 8. Cue-type components common to all conditions. Top row: statistical contrasts testing the difference between “+” and “H” cue trials, separately for Baseline/Invalid-Cue (left) and Valid-Cue (right) conditions. Middle and bottom row: average IC activations for IC 6 (middle) and IC 9 (bottom). The blue dots represent time points where the statistical contrast shown in the top panel is reliable by bootstrap test.

The components common to both conditions expressed the contrast at roughly comparable latencies, though the contrast was stable earlier for IC 6 (~160ms-200ms, 400ms-900ms for IC 6, 400ms-900ms for IC 9). The components unique to the Valid-Cue condition expressed the contrast at 500ms-850ms (IC 1) and 400ms-800ms (IC 3). Visually, the time-series for IC 3 is most similar to the P3-like morphology observed in electrode space.

Figure 9. Cue-type components unique to the Valid-Cue condition. Top row: statistical contrasts testing the difference between “+” and “H” cue trials, separately for Baseline/Invalid-Cue (left) and Valid-Cue (right) conditions. Middle and bottom row: average IC activations for IC 1 (middle) and IC 3 (bottom). The blue dots represent time points where the statistical contrast shown in the top panel is reliable by bootstrap test.

Behavioral PLS

Behavioral PLS analysis of low-contrast trials over the ISI with z-scored accuracy as the behavior of interest yielded one significant LV. The LV did not differentiate between conditions and indicated strong negative correlation between ERP amplitude and accuracy across conditions. The expression of this LV overlapped somewhat with the LV described above, with regions of stability over the vertex (Cz) and left lateral parietal-occipital (PO7) electrodes. However, its expression was delayed (400-700ms) and additionally included fronto-central and right frontal electrodes (FC4, Fz/F2/F4).

Post-grating effects

Mean-centering ST-PLS was also performed on 250ms-long low-contrast trial epochs time-locked to grating onset to investigate whether the informative value of the cue stimulus would translate to differential early visual processing of the grating stimulus. Note that in this analysis Baseline and Invalid-Cue conditions were merged to increase statistical power. This was deemed acceptable because a preliminary analysis showed no significant differences between these two conditions over the same epoch ($p < 0.804$, not shown). The contrast between the merged Baseline and Invalid-Cue conditions and the Valid-Cue condition was significant ($p < 0.025$, 100% cross-block covariance). The Valid-Cue condition was characterized by enhanced negativity over the vertex and an enhanced positivity over parietal-occipital electrodes, emerging approximately 30-60ms and 120-170ms post-stimulus.

A battery of analyses aimed at using VEP amplitude/latency to index stimulus contrast and contrast sensitivity was ultimately unsuccessful. Stimulus-dependent differences could be not established using mean amplitude and peak latency measures from a variety posterior electrodes, nor could they be correlated with behavior.

Discussion

Behavior

The behavioral results were identical to those of de la Rosa et al. (in press). The addition of an unpredictable high-contrast grating in the Invalid-Cue condition was associated with decreased identification accuracy for low-contrast gratings relative to Baseline, presumably because of a tonic reduction in sensory gain. When the high-contrast grating was made predictable as in the Valid-Cue condition, identification accuracy for low-contrast gratings recovered to Baseline levels. The introduction of a fully informative cue for high-contrast gratings allowed flexible tuning of sensory gain on a trial to trial basis such that task performance could be maintained at optimal levels due to enhanced contrast sensitivity on low-contrast trials while sensory overload could be prevented by diminished sensitivity on high-contrast trials (de la Rosa et al., in press). The alternative view that the cue is utilized as part of an avoidance strategy was shown to be untenable by Experiment II because the original effect persevered even when participants were forced to make a perceptual decision about high-contrast stimuli (which they succeeded in doing at above-chance levels).

Event-Related Potentials

The goal of the first set of analyses was to isolate task-dependent changes in brain electrical activity by capturing a stable spatiotemporal pattern of cortical potentials that differentiated the Valid-Cue condition from the Baseline and Invalid-Cue conditions in the interval between cue and grating onset. Such an effect was observed both at the vertex and bilaterally over parietal-occipital electrodes. The effect had a similar time-course (200-550ms) and magnitude at the two topographic regions, but opposite polarity. In general, waveform segments associated with the effect roughly corresponded to the P2-N2-P3 complex, as well as a late slow wave. The Valid-Cue condition was characterized by lower absolute amplitude relative to other conditions at all sites. An examination of the waves computed by taking the difference between the Valid-Cue and Baseline

conditions revealed that their amplitude distribution was highly time-dependent, implying that the aforementioned task difference may not reflect a unitary process.

Complementary analysis in component space revealed the effect to be reliably expressed by two distinct independent components, suggesting that this task difference is comprised of at least two stages of information processing. The expression of the effect was most prominent at left parietal-occipital channels early (IC 1) and over central-parietal channels late (IC 3).

In a second set of analyses we sought to examine what effectively amounted to an interaction between cue type (“H” versus “+”) and task (Baseline/Invalid-Cue versus Valid-Cue). Namely, the goal of the exercise was to pursue the notion that differences in brain activity related to cue type would be modulated in a task-dependent manner, in parallel with their informative value. Multivariate analyses in electrode space failed to yield any obvious differences in terms of scalp distribution (central-parietal in both tasks), but did suggest that the effect was greater in magnitude in the Valid-Cue condition. Unfortunately, this approach allowed neither a direct comparison of the effects nor an estimate of how they may have been impacted by the differential probability of the cue stimuli (the “+” cue appeared in 66% of the trials, or at twice the frequency of the “H” cue). Analysis in component space enabled us to continue our inquiry by addressing both of these concerns. We reasoned that any contribution of an “oddball”-type response would be roughly equal across tasks. In addition, if the statistical contrasts denoting differences in cue type reflect the contribution of several underlying electrogenic processes with independent time courses – some of which are task-specific – then it should be possible to isolate them in separate components.

Indeed, the analysis revealed two components (IC 6 and IC 9) that commonly expressed the contrast between “+” and “H” cues in both Baseline/Invalid-Cue and Valid-Cue conditions, and two components (IC 1 and IC 3) that uniquely expressed such a contrast only in the Valid-Cue condition. These findings are consistent with the notion that information conferred by the valid cue is uniquely utilized in some preparatory fashion. Interestingly, the two components that uniquely captured the effect of cue type in

the Valid-Cue condition also captured the main task effect described above (Valid-Cue versus Baseline/Invalid-Cue).

The tentative interpretation offered here is that the task differences demonstrated by these analyses may reflect differential states of cognitive processing with direct perceptual consequences. Behavioral data leave little doubt that Valid-Cue identification accuracy (and by implication, contrast sensitivity) was modulated by knowledge conveyed by the cue. Although theoretically sensory gain was also adjusted in the Baseline and Invalid-Cue conditions as a result of task instruction, there is no reason to suspect this adjustment to be time-locked to the cue as in the Valid-Cue condition. The adjustment of sensory gain critically depends on cue type only when the cue has some informative value.

Therefore, the main effect of task (Valid-Cue versus Baseline/Invalid-Cue) as well as the cue type-task interaction should reflect a difference between adjusting and not adjusting sensitivity in response to the cue. The fact that these effects have common spatiotemporal expression indicates that they differentiate between cognitive states in which the information conferred by the cue is utilized in some way, rather than simply registering the potential utility of the cue. In other words, the electrophysiological effects reported here reflect knowledge-driven, top-down modulation of contrast sensitivity. Such a view is particularly supported by the outcome of the behavioral PLS analysis, which established a link between activity in this interval and task performance, as well as the fact that both statistical effects could be traced to the same independent components.

In terms of wave morphology and spatiotemporal expression, the effects we report bear some similarity to “classic” ERP components. The dominant task-related patterns were those that manifested early in parietal-occipital regions (IC 1) and later in central-parietal regions (IC 3). These correspond quite well to the visual N2 and P3, respectively, in both topography and latency (Simson et al., 1977). The relatively long-latency P3 (~500ms) observed in this experiment is consistent with previous literature (Simson et al., 1977; Squires et al., 1977; Perrault & Picton, 1984). The emergence of endogenous waves such as the N2-P3 complex typically signals broad stages of cognitive processing

(Hillyard & Picton, 1987), including putative early steps such as registering the onset of an informative stimulus (Picton & Hillyard, 1974) and later, more involved evaluative steps (Picton, 1992). The N2 in particular is associated with perceptual stimulus evaluation and classification (Ritter et al., 1979) because it has a modality-dependent topography (Simson et al., 1977) and because it heralds P3 onset, which reflects a later phase of processing (Hillyard & Picton, 1987).

The negative slow potentials observed at the vertex come as no surprise, given the nature of the task. Almost any task in which a warning stimulus precedes a task-relevant imperative stimulus will evoke some form of surface-negative slow wave during the foreperiod, often referred to as Contingent Negative Variation (CNV; Walter et al., 1964). However, the task described here differs from typical CNV experiments in several important ways. One, the cue and the grating had considerably longer duration than the typical CNV S_1 and S_2 . Two, most CNV paradigms are simple RT tasks. In this experiment, participants were explicitly instructed to prioritize response accuracy over response speed. Differential effects of such “sensory set” versus “motor set” instructions are well documented (Loveless & Sanford, 1974). Three, the 500ms ISI in this task was on the low end of typical CNV foreperiods which can last up to a few seconds. In other words, the gain-control slow wave effect may be part of the CNV family, but due to a disparity of task parameters it is difficult to make a direct comparison.

This is unfortunate, because the CNV is viewed as two somewhat dissociable entities: an early fronto-central component related to cognitive processing of the cue (an orienting, “O-wave”) and a later centroparietal component related to motor preparation (an expectancy, “E-wave”; Rohrbaugh et al., 1976, 1986). The gain-control effect appears relatively early in the ISI and in that sense bears some similarity to the O-wave. Conversely, it is likely that cortical potentials related to motor preparation were minimized (in the ISI) given the emphasis on accuracy over speed. This is consistent with the symmetrical amplitude distribution of the effect, as well as the lack of consistent RT patterns.

The idea that the O-wave reflects sensitization is by no means novel. For example, Loveless (1975) observed that O-wave amplitude changes mirror changes in sensitivity. He suggested that this cortical potential may reflect the regulation of sensory gain. What is particularly interesting to note then is that gain-control slow wave amplitude was *smaller* in the Valid-Cue condition, where sensitivity was equal or higher than in the other two conditions. Though some authors have held that increased processing or an enhanced state of attention tends to elicit higher-amplitude CNV (Tecce, 1972), amplitude has rarely been found to correlate with subsequent performance (Hillyard & Picton, 1987). Hillyard (1973) surmised that “the degree to which the CNV predicts subsequent perceptual sensitivity is rather meager” (p165) and this view has undoubtedly held true with few exceptions. To our knowledge there has been no recorded instance where reduced amplitude was concomitant with more effective performance.

This reduction of slow wave amplitude may reflect knowledge-driven modulation of sensory gain at the subcortical level. In a series of studies, Skinner and Yingling (1976, Yingling & Skinner, 1975) showed that slow cortical potentials are related to slow potentials across a series of subcortical networks that mediate thalamo-cortical sensory transmission. The major point of influence was shown to be nucleus reticularis thalami that envelops the thalamus and forms inhibitory GABAergic connections. Stimulation of the nucleus reticularis induces inhibition of the thalamic relay nuclei, including the lateral geniculate, and effectively abolishes visual evoked potentials in occipital visual areas (Skinner & Yingling, 1976). One way in which thalamic activity is regulated is via the mediotthalamic-frontocortical system (MTFC). The MTFC is comprised of reciprocal connections between the frontal cortex and the nucleus reticularis and has a phasic, stimulation-dependent excitatory effect on the latter (Yingling & Skinner, 1975). Stimulation of the MTFC afferent to the nucleus reticularis elicits positive potentials in the nucleus reticularis and negative potentials over the frontal cortex.

It has since been speculated that the thalamic reticular nucleus acts as a gating mechanism to regulate the reciprocal flow of sensory information between the thalamus and cortex (Skinner & Yingling, 1977). More importantly, the consensus has been that cortical slow potentials such as the CNV reflect the activity of a central system in the

frontal cortex that regulates and filters sensory transmission in thalamocortical loops (Birbaumer et al., 1990; Brunia & Van Boxtel, 2001; Elbert & Rockstroh, 1987; Skinner & Yingling, 1976, 1977). Recent imaging work supports the notion that thalamic activity is closely associated with slow cortical potentials (Nagai et al., 2003), though several other regions have also been implicated, most notably the anterior cingulate (Ioannides et al., 1994; Liu et al., 1996).

Therefore, a plausible explanation for the reduced amplitude in the Valid-Cue condition could be that the MTFC is briefly suppressed in an effort to upregulate the flow of sensory information to visual cortex by disinhibition of the thalamus. From a functional perspective this interpretation is consistent with some current opinions of thalamic sensory gating. For example, some authors have posited that slow potentials reflect a thalamic tuning of thresholds for cortical excitability (Birbaumer et al., 1990). In the extreme, such tuning helps to prevent seizure-like hyperexcitation, but it can also facilitate attentional filtering. The second experiment reported in De la Rosa et al (in press) demonstrated that the behavioral gain-control effect may indeed serve to protect against sensory overload.

One alternative interpretation of these task-dependent differences could be that they signify a contrast between attending to the cue in Valid-Cue trials versus not attending to the cue in Baseline and Invalid-Cue trials. In other words, notwithstanding the behavioral outcome, this LV may have captured a simple orienting response to the cue only when it was task-relevant (Sokolov, 1963). However, this explanation appears to be unlikely for two reasons. One, if participants had some heightened perceptual sensitivity to the cue due to its task relevance then this should have been reflected in early sensory components, such as N1 (Hillyard et al., 1973). The statistical effect denoted by the LV only becomes stable some 200ms following cue onset. Likewise, ST-PLS over an epoch time-locked to cue presentation but short enough only to include the exogenous ERP components revealed no significant effects. Two, accuracy was comparable in Valid-Cue and Baseline conditions, indicating that participants were definitely “on-task” in the former. This argument would imply that participants in the Baseline condition were

selectively attending to the grating but not to the cue. Given the relatively rapid presentation of stimuli and the overall pace of the trials this seems highly implausible.

Another alternative interpretation of the observed effects could be that in the Valid-Cue condition the cue allows one to modify potential response mappings (narrowing down three possible responses to just two) and/or to conjure representations of the possible target gratings. A response mapping explanation is unlikely because the effect is expressed relatively early in the ISI (200-550ms) whereas the imperative stimulus does not appear until much later (1050ms). In addition, the topography of the effect is inconsistent with a process that facilitates response preparation, because it is more reliably expressed over central and central-parietal channels than over fronto-central ones. A visual working memory explanation is also unlikely because sustained positivity associated with maintenance tends to develop considerably more anterior to the vertex (Drew, McCollough, & Vogel, 2006).

Finally, analyses of grating-related activity also demonstrated a differential effect of cue validity on stimulus processing. Early stimulus-bound components observed at 30-60ms (C1) and 120-170ms (P1) all exhibited greater amplitudes in the Valid-Cue condition. Given that early components are known to be highly sensitive to physical characteristics of the stimulus such as contrast, this result suggests that representation of contrast in the Valid-Cue condition was enhanced. The finding that the C1 and P1 components of the VEP were modulated by task differences suggests that the gain effect manifested in both striate (primary visual area) and dorsal extrastriate cortex, respectively (Di Russo et al., 2001; Jeffreys & Axford, 1972a,b).

However, this could not be corroborated using behavioral measures, as no consistent relationship could be established between VEP mean amplitude/latency and identification accuracy. Likewise, the measures that we employed do not appear to be sensitive in detecting perceptual changes to the contrast increments used (19% and 26%). This is perhaps unsurprising given the difficulty of the task, as evidenced by the fairly low identification accuracies. Another explanation could be that an insufficient number of measurements were taken to isolate differences in VEPs related to stimulus contrast.

Much work remains to be done to fully explore the rich nature of this data set and the effect that it ostensibly demonstrates. The idea that the gain-control effect may be expressed by multiple independent generators must be pursued further. In addition, the present conclusions are speculative at best regarding the electrogenic source of the effect without a systematic source analysis. These data offer information about the time-course of the effect that will be critical in the design of any future studies of this phenomenon using complementary techniques with finer spatial resolution such as functional MRI. The discovery that top-down modulation of sensory gain is associated with reduced amplitude of endogenous ERP components is novel and points to a possible cortical-subcortical interaction as the physiological bridge between “top-down” and “bottom-up” modes of information processing.

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