Elevated arousal levels enhance contrast perception

Dongho Kim
Department of Psychological and Brain Sciences,
Boston University, Boston, MA, USA

Savannah Lokey
Department of Psychological and Brain Sciences,
Boston University, Boston, MA, USA

Sam Ling
Department of Psychological and Brain Sciences,
Boston University, Boston, MA, USA

Our state of arousal fluctuates from moment to moment—fluctuations that can have profound impacts on behavior. Arousal has been proposed to play a powerful, widespread role in the brain, influencing processes as far ranging as perception, memory, learning, and decision making. Although arousal clearly plays a critical role in modulating behavior, the mechanisms underlying this modulation remain poorly understood. To address this knowledge gap, we examined the modulatory role of arousal on one of the cornerstones of visual perception: contrast perception. Using a reward-driven paradigm to manipulate arousal state, we discovered that elevated arousal state substantially enhances visual sensitivity, incurring a multiplicative modulation of contrast response. Contrast defines vision, determining whether objects appear visible or invisible to us, and these results indicate that one of the consequences of decreased arousal state is an impaired ability to visually process our environment.

Introduction

How do arousal states govern behavior? Arousal levels are largely regulated by the locus coeruleus–norepinephrine system, a component of the ascending reticular activating system (Aston-Jones & Cohen, 2005b; Moruzzi & Magoun, 1949; Sara, 2009). This system, which is also believed to play a role in governing vigilance (Berridge, 2008; Carter et al., 2010) and stress responses (Valentino & Van Bockstaele, 2008), projects widely throughout the brain and is believed to influence a host of cognitive processes (Sara, 2009). Despite the ubiquitous role that arousal seems to play in affecting behavior, the mechanism by which arousal state modulates representations remains unclear. While some have theorized that arousal levels modulate the gain of neural responses (Aston-Jones & Cohen, 2005a; Gayet, Paffen, Belopolsky, Theeuwes, & Van der Stigchel, 2016; Mather, Clewett, Sakaki, & Harley, 2015), only a handful of studies have directly tested this intriguing hypothesis (Cano, Bezdudnaya, Swadlow, & Alonso, 2006), particularly in humans (T.-H. Lee, Baek, Lu, & Mather, 2014; T. H. Lee, Sakaki, Cheng, Velasco, & Mather, 2014; Phelps, Ling, & Carrasco, 2006). In this study, we examined how reward-driven arousal states affect the human contrast response. The contrast response function is one of the most well-characterized neural responsivity profiles in vision, mapping the nonlinear relationship between the physical contrast of a signal and its resultant neural response (Ohzawa, Sclar, & Freeman, 1982). This gain profile plays a primary role in determining what we can and cannot see in our visual environment, and the shape of this function has already proven itself to be malleable to a number of cognitive processes, including attention (Cameron, Tai & Carrasco, 2002; Carrasco, Ling, & Read, 2004; Herrmann, Montaser-Kouhsari, Carrasco, & Heeger, 2010; Ling & Carrasco, 2006a, 2006b; Reynolds & Chelazzi, 2004; Reynolds & Heeger, 2009) and competition (Ling & Blake, 2012; Moradi & Heeger, 2009). Although there is evidence to suggest that arousal states alter human perception (Keil et al., 2003; T.-H. Lee, Baek et al., 2014; T. H. Lee, Sakaki et al., 2014; Lojowska, Gladwin, Hermans, & Roelofs, 2015; Phelps et al., 2006; Woods, Philbeck, & Wirtz, 2013), very little work has directly explored how arousal levels might influence the contrast response profile (Cano et al., 2006; Zhuang et al., 2014), particularly in humans (Song & Keil, 2014). Some theorize that the slope of a response profile becomes steeper with arousal level (Aston-Jones & Cohen, 2005a), which would increase discriminability straddling a certain range of intensities. However, other

Citation: Kim, D., Lokey, S., & Ling, S. (2017). Elevated arousal levels enhance contrast perception. *Journal of Vision*, *17*(2):14, 1–10, doi:10.1167/17.2.14.

doi: 10.1167/17.2.14 Received October 30, 2016; published February 28, 2017 ISSN 1534-7362 Copyright 2017 The Authors

reports from animal models suggest instead that contrast responsivity increases multiplicatively when alertness is high, effectively boosting the overall signal-to-noise ratio (Cano et al., 2006). In this study, we employed psychophysical measures of contrast sensitivity to evaluate these competing hypotheses, examining the role that arousal level plays in altering contrast sensitivity in humans. In particular, we assessed how arousal alters the shape of the contrast psychometric function, quantifying the specific gain changes brought about by arousal.

To manipulate arousal, we divided participants into two groups: high-arousal and low-arousal. One group—high-arousal—was asked to refrain from eating and drinking for 5 hr prior to the experiment. The other group (low-arousal) was allowed normal access to eating and drinking, and was given a cup of water prior to the experiment. During the psychophysical experiment, both groups received drops of water at 80% probability coincident with stimulus presentation throughout the experiment. Water during the experiment arouses participants differently, depending on deprivation history: Under deprivation the water drops lead to high levels of arousal, and under satiation they lead to lower levels of arousal. Importantly, because we were simply interested in manipulating arousal state, the likelihood of water delivery was not contingent on a participant's response. This differs from traditional reward paradigms, allowing for purer arousal manipulation (Kim, Seitz, & Watanabe, 2015; O'Doherty, Deichmann, Critchley, & Dolan, 2002).

Experiment 1: Does arousal affect contrast perception?

Methods

Participants

Participants consisted of 46 healthy male and female volunteers, ages 18–23, with normal or corrected-to-normal vision. Sample sizes in our experiment was determined based on simulation-based power analyses, with $\alpha = 0.05$ and power of 0.80 for between-groups comparison; a minimum of 16 participants per group was needed, given an effect size of 0.52 (Cohen's *d*). All participants were undergraduates at Boston University, and gave informed consent in the protocol that was approved by the institutional review board at Boston University.

Materials and apparatus

Visual stimuli were generated on a gamma-corrected, 19-in. CRT display (100-Hz refresh), with the monitor's mean luminance (42 cd/m^2) providing the only source of illumination in an otherwise dark testing chamber. Participant's heads were stabilized with a chin and forehead rest, 57 cm from the display. All aspects of the experiment—display generation, trial sequences, and staircase procedure—were controlled using MATLAB and the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) running on a Mac Mini.

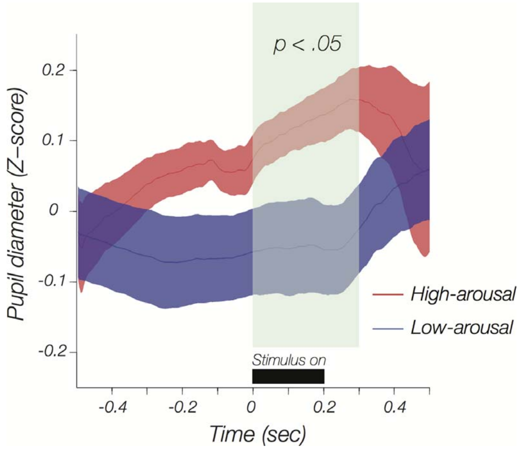

Figure 1. Reward value increases stimulus-evoked pupillary response diameter. The red curve indicates mean pupil dilation from the high-arousal (deprived) group, and the blue curve represents mean pupil dilation from the low-arousal (non-deprived) group. Shaded regions represent standard errors. The black bar corresponds to visual-stimulus duration (200 ms). The green-shaded region of a 300-ms time window (the stimulus duration plus an additional 100-ms lag) was used for statistical analysis. Pupil diameter was normalized relative to the mean of the pupillometry time series. We calculated means of pupil dilations within the time window for *t* tests. Note that the increase in diameter prior to the stimulus onset was simply due to the anticipation of an upcoming stimulus, which had a predictable timing.

Procedure

To optimize contrast parameters for each participant such that we fully captured their dynamic range, an initial titration procedure was conducted to customize the ranges of contrasts tested for each individual participant, without water delivery. Specifically, we used an adaptive staircase procedure (QUEST; Watson & Pelli, 1983) to measure participants' contrast threshold for performing a two-alternative forced-choice fine orientation-discrimination task (±2° relative to vertical) on an oriented Gabor stimulus at fixation (subtending 4° of visual angle, 1 c/°), at 75% accuracy (Figure 2B). We acquired four staircases, each of which was 40 trials, and the average of these contrast thresholds gave us a ballpark estimate of the range of contrasts needed to fully capture the dynamic range of

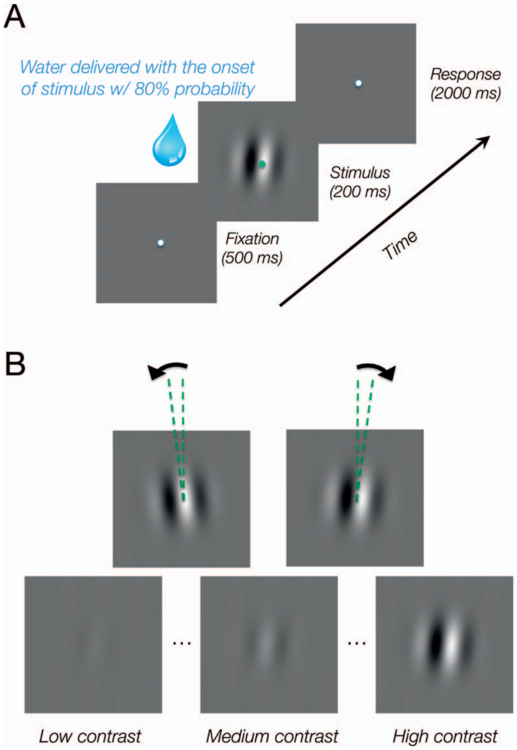

Figure 2. Task schematic and examples of orientation stimuli with different contrast levels. (A) A typical trial sequence in the experiment. (B) In a given trial, the target stimulus was tilted either clockwise or counterclockwise with respect to vertical, and participants were asked to report whether the grating was oriented clockwise or counterclockwise relative to vertical (upper row). To measure sensitivity as a function of contrast, the physical contrast of the stimuli varied from trial to trial, from very low to high (lower row).

the psychometric function per participant. Once the contrast threshold was established, we proceeded to the main experiment, in which we asked participants to perform a fine orientation-discrimination task on a grating stimulus that varied in contrast from trial to trial. The set of contrasts tested differed per participant, relying on their measured contrast threshold as a center point for a set of nine contrasts that were evenly spaced on a log scale, straddling the threshold contrast ($M = 8.9\%$ contrast, $SD = 0.12$). This was done to ensure that each participant's data set spanned the entire dynamic range, as well as to achieve saturation of the psychometric function.

Each trial started with a 500-ms fixation period in which participants gazed upon a small white dot (0.2° in diameter) at the center of screen. Then the fixation dot turned green and a target orientation stimulus was presented for 200 ms. As soon as the target was presented, participants had 2,000 ms to respond with a key press regarding whether the stimulus was oriented clockwise or counterclockwise with respect to vertical (Figure 2A). We collected 40 trials per condition.

To experimentally manipulate arousal, we adapted-a liquid reward-delivery paradigm commonly used in incentivized learning tasks (Imai, Kim, Sasaki, & Watanabe, 2014; Kim, Ling & Watanabe, 2015; O'Doherty et al., 2002; O'Doherty et al., 2004; O'Doherty, Dayan, Friston, Critchley, & Dolan, 2003; Seitz, Kim, & Watanabe, 2009). Such rewards have previously been shown to have both incentivizing and arousing properties (Bijleveld, Custers, & Aarts, 2009; Bray, Rangel, Shimojo, Balleine, & O'Doherty, 2008; Das, 2015). In our experiments, unlike most previous applications, liquid delivery was not task contingent, providing an incidental manipulation of arousal without operating as an incentive. Under this paradigm, participants were divided into two groups: high-arousal and low-arousal. The high-arousal group was asked to refrain from eating and drinking for 5 hr prior to the experiment. The low-arousal group was allowed normal access to eating and drinking and was given water prior to the experiment. During the psychophysical experiment, both groups received drops of water at 80% probability coincident with stimulus presentation throughout the experiment. Importantly, because we were simply interested in manipulating arousal state, note that the likelihood of water delivery was not contingent on a participant's response ("free reward"), unlike traditional reward paradigms, thereby allowing for a purer arousal manipulation. Participants were explicitly told that the liquid rewards arrived independent of performance. Water during the experiment aroused participants differently, depending on deprivation history: Under deprivation, water drops lead to high levels of arousal, and under satiation, they lead to lower levels of arousal. Water was delivered using a ValveLink 8.2 Liquid Delivery System (AutoMate Scientific, Berkeley, CA), which controlled the precise delivery of water to the participant, through an FDA-approved sterilized tube that extended into the participant's mouth. In our experiments, each reward instance involved the delivery of ~0.67 ml of water, for 200 ms. Across a 1-hr session, ~200 ml was delivered in total. This type of manipulation has been shown to effectively alter arousal, increasing pupil diameter as a function of reward value (Bijleveld et al., 2009). Importantly, because we were simply interested in manipulating arousal state, the likelihood of water delivery was not contingent on a participant's response. Because there is no response contingency for the water delivery, this differed from traditional reward protocols, allowing for a purer arousal manipulation and avoiding confounds with certain cognitive factors such as motivation and attention. To rule out spatial attention as a confounding factor, the stimulus location was always fixed, with no uncertainty. Because the liquid delivery was not contingent on behavioral performance, motivation and effort were precluded as confounding factors. Thus, effects we observed are attributed to the specific arousal manipulation.

Results

Stimulus-evoked pupil-diameter changes with arousal state

As an independent validation of the efficacy of the water-delivery protocol at altering arousal levels, we conducted pupillometry measurements in a separate set of 14 participants (Figure 1), to compare stimulus-evoked pupil dilation to the liquid rewards. Arousal state has been linked to pupil changes (McGinley et al., 2015; Reimer et al., 2014; Vinck, Batista-Brito, Knoblich, & Cardin, 2015), with previous work showing a strong link between pupil diameter and neural responses within the locus coeruleus–norepinephrine system (Wang & Munoz, 2015). Throughout the experiment, participants were instructed to maintain fixation on a central fixation point, and performed a two-alternative forced-choice orientation-discrimination task on a stimulus of fixed contrast (20% Michelson contrast). To measure pupil dilation, the pupil was monitored from the left eye using an EyeLink II eye-tracking system at a sampling rate of 250 Hz. We removed eyeblinks, as well as an additional 50 ms of data after blink, and further processed data by excluding spikes that were not in a predetermined range ($-3 < z$ score < 3) after applying z score to the derivative of the time series of the pupil data. Our results square with existing literature, revealing that stimulus-evoked pupil diameter is dependent on deprivation history: The high-arousal group demonstrated a larger stimulus-evoked pupillary response to the water stimulus than the low-arousal group, $t(14) = 2.56$, $p = 0.028$, two-sample t test, two-tailed. Interestingly, when we split the pupillometry time series into first and second halves, we found that there was no interaction between the high-arousal group and the low-arousal group and time, $F(1, 14) = 0.049$, $p = 0.8$, indicating that the arousal level of the high-arousal group was greater than that of the low-arousal group in the first half as well as the second half of the task. However, mean pupil diameter decreased over time, $F(1, 14) = 27.5$, $p < 0.01$, in both the high-arousal and low-arousal groups. This could be driven by a general novelty-driven increase in arousal across both high-arousal and low-arousal groups in response to the water delivery, which peters off for both groups. While other cognitive factors such as attention have been suggested to influence pupil diameter as well (Gabay, Pertzov, & Henik, 2011; Wierda, van Rijn, Taatgen, & Martens, 2012), in this study spatial and feature-based attention was held constant, and thus any observed effects are attributed to the specific arousal manipulation.

Reward-driven arousal state alters contrast sensitivity

To examine how arousal level influences contrast perception, we measured contrast psychometric functions in the deprived (high-arousal) and nondeprived (low-arousal) groups, with both groups receiving drops of water at 80% probability coincident with stimulus presentation. Participants performed a fine orientation-discrimination task on a grating stimulus appearing at fixation that varied in contrast from trial to trial. To fully capture each participant's dynamic range, we titrated the set of contrasts tested per individual prior to testing (for details, see Methods). Using the method of constant stimuli, we measured the psychometric function, a behavioral measure that scales proportionally to the signal-to-noise ratio of the underlying neural contrast response function (Britten, Shadlen, Newsome, & Movshon, 1992; Cameron et al., 2002; Celebrini & Newsome, 1994; Herrmann et al., 2010; Ling & Blake, 2012; Ling & Carrasco, 2006a, b; Parker & Newsome, 1998; Pestilli, Ling, & Carrasco, 2009; Shadlen, Britten, Newsome, & Movshon, 1996). Specifically, changes in the neural contrast response function under this framework directly affect an observer's ability to discriminate orientation changes in the probe that would, in turn, be reflected in corresponding changes to the behavioral psychometric functions. Importantly, the fine orientation discrimination was also designed such that psychometric functions did not saturate at perfect accuracy for most participants, allowing "headroom" to measure potential changes in the asymptote of the function with arousal level. In this design, the stimulus location and base orientation were fixed throughout the experiment. Because attentional allocation was held constant, it was precluded from playing a potential confounding role.

To quantify the shape of the psychometric function, each participant's accuracy was converted to d' units (Green & Swets, 1989) and fitted with Naka–Rushton functions (Naka & Rushton, 1966), quantifying the nonlinear relationship between stimulus input and response output. The results of these fits allowed us to quantitatively assess changes in the shape and magnitude of functions between the high-arousal and low-arousal conditions, in each participant. In particular, this model allowed us to quantify changes in the asymptote of the psychometric function ($R_{\max}$ parameter), which is a metric for the response gain of the underlying contrast response function; the semisaturation constant ($C50$ parameter), which is a metric for underlying contrast sensitivity; and the slope (n), which is a metric for sensitivity to changes in contrast within a given range. Fits across participants and conditions were high (mean R^2: high-arousal $= 0.88$, low-arousal $= 0.86$), and we observed no difference in goodness of fit between conditions, $t(44) = 0.8836$, $p = 0.38$.

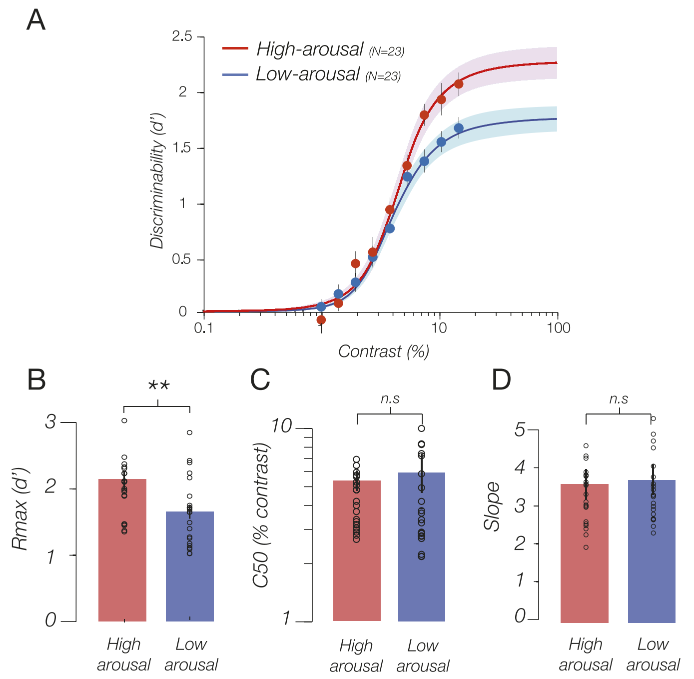

Figure 3. Results revealing the influence of arousal level on the psychophysical contrast response function. (A) Psychometric functions based on mean parameter estimates fitted per individual participant. Shaded area corresponds to 95% confidence interval. Data points correspond to mean performance and standard error, normalized to the maximum contrast per participant. (B) Arousal level significantly boosts the asymptote (R_{max}). Arousal level did not have a significant impact on the semisaturation constant ($C50$; C) or the slope (n; D). Points correspond to individual subject fitted parameter estimates.

Figure 3A depicts the pooled results from 46 observers (23 deprived and 23 nondeprived), revealing that high-arousal states increased asymptotic sensitivity, consistent with a response-gain modulation. More specifically, those in the deprived (high-arousal) group yielded psychometric functions that saturate (R_{max}) significantly higher than those in the nondeprived (low-arousal) group, $t(44) = 2.823$, $p < 0.01$, two-sample t test, two-tailed (Figure 3B), consistent with an increase in the responsivity of the underlying contrast response. A nonparametric bootstrap test also confirmed that this difference in R_{max} was significantly different between the high-arousal and low-arousal groups (95% confidence interval [0.17, 0.87]). Interestingly, however, our results revealed no difference in the semisaturation constant ($C50$) or the slope (n) between the two groups—$C50$: $t(44) = -0.32$, $p = 0.74$; n: $t(44) = -0.19$, $p = 0.85$; two-sample t test, two-tailed (Figure 3C and D). Taken together, these findings suggest that arousal alters the gain of early visual perception strictly by multiplicatively boosting overall responsivity to stimuli.

Experiment 2: Deprivation alone does not affect contrast perception

To rule out the possibility that our deprivation manipulation alone could have affected visual responses, we conducted an additional control experiment, in the absence of any liquid rewards. This experiment was identical to the main experiment, whereby one group of participants refrained from eating or drinking for 5 hr and another group did not. The only distinction was that participants did not receive the liquid reward during the psychophysical paradigm. If the results in Experiment 1 are truly due to arousal-state difference driven by our manipulation of the combination of deprivation history and liquid reward, rather than simply to deprivation alone, then we would expect no difference in psychometric functions in the absence of liquid rewards.

Methods

Participants consisted of 34 (17 deprived, 17 nondeprived) healthy male and female volunteers, ages 18–23, with normal or corrected-to-normal vision. Sample sizes in our experiment were determined based on simulation-based power analyses, with $\alpha = 0.05$ and power of 0.80 for between-groups comparison; a minimum of 16 participants per group was needed, given an effect size of 0.52 (Cohen's d). All participants were undergraduates of Boston University, and gave informed consent in the protocol that was approved by the institutional review board at Boston University. Visual stimuli were identical to those of Experiment 1, as was the procedure; contrast psychometric functions were assessed for two groups—one deprived and one nondeprived—but here participants were not given liquid rewards during the psychophysical task.

Results

In the absence of liquid rewards, our results verified that there was no significant influence of deprivation state alone on the contrast response—R_{max}: $t(32) = -0.24$, $p = 0.82$; $C50$: $t(32) = 0.68$, $p = 0.5$; n: $t(32) = 0.58$, $p = 0.56$; two-sample t test, two-tailed (Figure 4). Fits across participants and conditions were high (mean R^2: high-arousal = 0.87, low-arousal = 0.85), and we observed no difference in goodness of fit between conditions, $t(32) = 0.5085$, $p = 0.61$. This suggests that the effects we observed in Experiment 1 were driven by the arousal-evoking combination of deprivation history *and* the liquid reward. Comparing conditions from Experiments 1 and 2, we also observed differences in

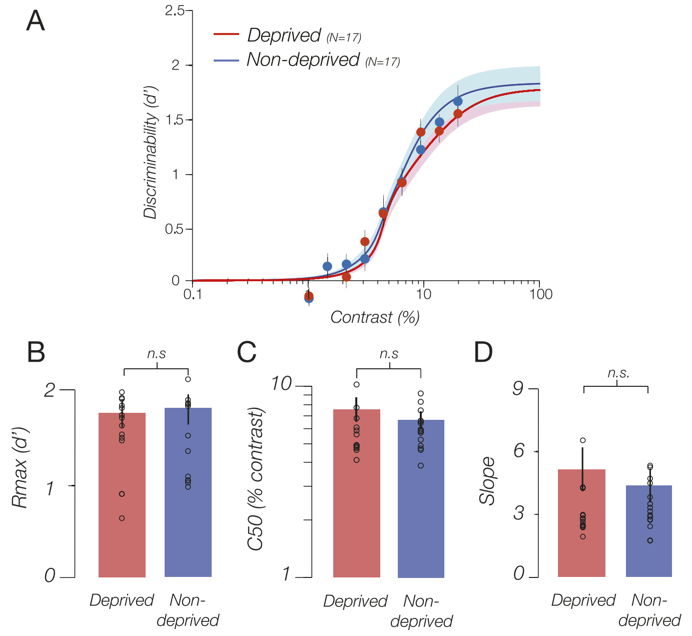

Figure 4. Results from Experiment 2, revealing the influence of deprivation alone on the psychophysical contrast response function. (A) Psychometric functions based on mean parameter estimates fitted per individual participant. Shaded area corresponds to 95% confidence interval. Data points correspond to mean performance and standard error, normalized to the maximum contrast per participant. Deprivation in the absence of rewards did not have a significant impact on the asymptote (R_{max}; B), the semisaturation constant (*C*50; C), or the slope (*n*; D). Points correspond to individual subject fitted parameter estimates.

contrast response functions between the deprived-rewarded group and deprived-nonrewarded group. The addition of water delivery appeared to increase the asymptotic (R_{max}) response, $t(38) = 2.3175$, $p = 0.026$, presumably simply due to increases in arousal with liquid stimulation.

General discussion

Arousal states can have profound impacts on behavior: Current estimates suggest that over 70,000 car-related injuries in the United States each year are attributed to driving under drowsy, low-arousal states (National Highway Traffic Safety Administration, U.S. Department of Transportation, 2011). What influence, though, does arousal have on visual responsivity? Using the contrast response as a test bed, our results suggest that low arousal substantially decreases the response gain of the underlying behavioral response function. Although further work will be needed to pinpoint the cortical or subcortical locus of our behavioral effects in humans, our current behavioral results square with animal work reporting that alertness levels have a multiplicative effect on the contrast response function of lateral geniculate nucleus neurons in rabbits (Cano et al., 2006). Interestingly, a growing body of recent electrophysiological studies in rodents has also found evidence to suggest that speed of locomotion multiplicatively increases the gain of responses in early visuocortical and subcortical areas (Erisken et al., 2014; Niell & Stryker, 2010)—an effect that some have suggested is also linked to arousal levels (Erisken et al., 2014). While processes such as attention have been shown to modulate subcortical responses in humans (Kastner, Schneider, & Wunderlich, 2006; Ling, Pratte, & Tong, 2015; Schneider & Kastner, 2009), the role that arousal plays in modulating subcortical visual areas remains to be tested.

Note that while our arousal manipulation does increase pupil diameter, this alone does not necessitate improvements in visual sensitivity, and is unlikely to explain our current results. Indeed, an increase in pupil size has been shown to generally impair contrast sensitivity, owing to increased spherical aberrations, wherein the largest impairments occur at high spatial frequencies (impairments emerge at >3–4 c/°; Campbell & Green, 1965). In addition, our stimuli were intentionally chosen to have a sufficiently low spatial frequency (1 c/°) that discriminability remained unaffected by changes in pupil size alone (Campbell & Green, 1965). Thus, the effects on visual sensitivity we observe here are likely to have emerged purely from reward-driven arousal, rather than changes in pupil diameter alone. Interestingly, previous work has found that emotionally driven increases in arousal enhance contrast thresholds at low spatial frequencies yet can impair contrast sensitivity for higher spatial frequencies (Bocanegra & Zeelenberg, 2009; Lojowska et al., 2015). While it is possible that arousal truly impairs sensitivity for high spatial frequencies at a cortical level, these observed impairments could also arise strictly as a result of an increase in pupil diameter, which is known to optically degrade the visual input to a larger degree for higher spatial frequencies.

What neural computations might drive changes in gain with arousal? One possible hypothesis is that this arousal-driven modulation is made possible through a tip in the balance between excitation and inhibition inherent to divisive normalization models, thereby altering neural responsivity and perceptual sensitivity. The link between divisive normalization and gain control has served as a cornerstone concept for computational models of early vision (Carandini & Heeger, 2011; Heeger, 1992; Ling & Blake, 2012; Ling, Jehee, & Pestilli, 2015; Ling, Pearson, & Blake, 2009; Pratte, Ling, Swisher, & Tong, 2013; Reynolds & Heeger, 2009), and more recent models have built on this idea, implicating normalization as the driving force behind sensory-gain modulation via processes such as attention (Carandini & Heeger, 2011; Reynolds & Heeger, 2009) and interocular competition (Ling & Blake, 2012; Ling, Hubert-Wallander, & Blake, 2010; Moradi & Heeger, 2009). Specifically, these normalization-based models of gain modulation rely on a simple idea: that increases in the gain of a visual response hinge on a release from inhibition. A similar force may be driving arousal-based modulation of perception: Arousal may enact a release from inhibitory mechanisms, and as a result boost the gain of a visual response and improve sensitivity to high-contrast stimuli. Although the neuromodulatory source of this gain modulation may come from multiple sites (S. H. Lee & Dan, 2012), animal work has begun shedding light on the cellular and neuromodulatory mechanisms underlying the boost in visuocortical gain with arousal in rodents, revealing that norepinephrine does indeed play a critical role in neural depolarization during arousal-heightening locomotion, a neuromodulatory role distinct from that of acetylcholine (Polack, Friedman, & Golshani, 2013).

Although attention and arousal are often considered linked processes, the origins of their modulatory signals are quite distinct. Arousal signals have primarily been attributed to the locus coeruleus–norepinephrine system, whereas the attentional-control signals stem from a cortical constellation encompassing both dorsal and ventral frontoparietal networks. Thus, while they are potentially complementary modulatory signals, it remains unclear as to whether these two processes influence response properties in the brain interactively or they act as two independent processes. Interestingly, attention researchers have long viewed arousal levels as a source of potential confounds in empirical studies of attention. Surprisingly, however, there is very little understanding of what mechanistic contribution arousal actually plays in attentional modulation. Future work may shed light on the interplay between attention and arousal modulation of the gain of response in humans.

Keywords: arousal, contrast response function, reward, visual perception

Acknowledgments

The authors would like to thank the members of the Ling Lab (FullyComputable) for their valuable comments. DK was supported in part by Basic Science Research Program through the National Research Foundation of Korea funded by the Ministry of Science, ICT & Future Planning (2016R1C1B2015901).

Commercial relationships: none.

Corresponding author: Sam Ling.
Email: samling@bu.edu.
Address: Department of Psychological and Brain Sciences, Boston University, Boston, MA, USA.

References

Aston-Jones, G., & Cohen, J. D. (2005a). Adaptive gain and the role of the locus coeruleus-norepinephrine system in optimal performance. *The Journal of Comparative Neurology*, *493*(1), 99–110, doi:10.1002/cne.20723.

Aston-Jones, G., & Cohen, J. D. (2005b). An integrative theory of locus coeruleus-norepinephrine function: Adaptive gain and optimal performance. *Annual Review of Neuroscience*, *28*, 403–450, doi:10.1146/annurev.neuro.28.061604.135709.

Berridge, C. W. (2008). Noradrenergic modulation of arousal. *Brain Research Reviews*, *58*(1), 1–17, doi:10.1016/j.brainresrev.2007.10.013.

Bijleveld, E., Custers, R., & Aarts, H. (2009). The unconscious eye opener: Pupil dilation reveals strategic recruitment of resources upon presentation of subliminal reward cues. *Psychological Science*, *20*(11), 1313–1315, doi:10.1111/j.1467-9280.2009.02443.x.

Bocanegra, B. R., & Zeelenberg, R. (2009). Emotion improves and impairs early vision. *Psychological Science*, *20*(6), 707–713.

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*(4), 433–436, http://doi.org/10.1163/156856897X00357.

Bray, S., Rangel, A., Shimojo, S., Balleine, B., & O'Doherty, J. P. (2008). The neural mechanisms underlying the influence of pavlovian cues on human decision making. *The Journal of Neuroscience*, *28*(22), 5861–5866, doi:10.1523/JNEUROSCI.0897-08.2008.

Britten, K. H., Shadlen, M. N., Newsome, W. T., & Movshon, J. A. (1992). The analysis of visual motion: A comparison of neuronal and psychophysical performance. *The Journal of Neuroscience*, *12*(12), 4745–4765.

Cameron, E. L., Tai, J. C., & Carrasco, M. (2002). Covert attention affects the psychometric function of contrast sensitivity. *Vision Research*, *42*(8), 949–967.

Campbell, F. W., & Green, D. G. (1965). Optical and retinal factors affecting visual resolution. *The Journal of Physiology*, *181*(3), 576–593.

Cano, M., Bezdudnaya, T., Swadlow, H. A., & Alonso, J.-M. (2006). Brain state and contrast sensitivity in the awake visual thalamus. *Nature Neuroscience*, *9*(10), 1240–1242, http://doi.org/10.1038/nn1760.

Carandini, M., & Heeger, D. J. (2011). Normalization as a canonical neural computation. *Nature Reviews Neuroscience*, *13*, 51–62, doi:10.1038/nrn3136.

Carrasco, M., Ling, S., & Read, S. (2004). Attention alters appearance. *Nature Neuroscience*, *7*(3), 308–313, http://doi.org/10.1038/nn1194.

Carter, M. E., Yizhar, O., Chikahisa, S., Nguyen, H., Adamantidis, A., Nishino, S., … de Lecea, L. (2010). Tuning arousal with optogenetic modulation of locus coeruleus neurons. *Nature Neuroscience*, *13*(12), 1526–1533, doi:10.1038/nn.2682.

Celebrini, S., & Newsome, W. T. (1994). Neuronal and psychophysical sensitivity to motion signals in extrastriate area MST of the macaque monkey. *The Journal of Neuroscience*, *14*(7), 4109–4124.

Das, A. (2015). Task-related responses in intrinsic-signal optical imaging. *Journal of Vision*, *15*(12): 1415, doi:10.1167/15.12.1415. [Abstract]

Erisken, S., Vaiceliunaite, A., Jurjut, O., Fiorini, M., Katzner, S., & Busse, L. (2014). Effects of locomotion extend throughout the mouse early visual system. *Current Biology*, *24*(24), 2899–2907, doi:10.1016/j.cub.2014.10.045.

Gabay, S., Pertzov, Y., & Henik, A. (2011). Orienting of attention, pupil size, and the norepinephrine system. *Attention, Perception, & Psychophysics*, *73*(1), 123–129.

Gayet, S., Paffen, C. L., Belopolsky, A. V., Theeuwes, J., & Van der Stigchel, S. (2016). Visual input signaling threat gains preferential access to awareness in a breaking continuous flash suppression paradigm. *Cognition*, *149*, 77–83.

Green, D. M., & Swets, J. A. (1989). *Signal detection theory and psychophysics*. Los Altos, CA: Peninsula Publishing.

Heeger, D. J. (1992). Normalization of cell responses in cat striate cortex. *Visual Neuroscience*, *9*(2), 181–197.

Herrmann, K., Montaser-Kouhsari, L., Carrasco, M., & Heeger, D. J. (2010). When size matters: Attention affects performance by contrast or response gain. *Nature Neuroscience*, *13*(12), 1554–1559, doi:10.1038/nn.2669.

Imai, H., Kim, D., Sasaki, Y., & Watanabe, T. (2014). Reward eliminates retrieval-induced forgetting. *Proceedings of the National Academy of Sciences, USA*, *111*(48), 17326–17329, doi:10.1073/pnas.1404469111.

Kastner, S., Schneider, K. A., & Wunderlich, K. (2006). Beyond a relay nucleus: Neuroimaging views on the human LGN. *Progress in Brain Research*, *155*, 125–143.

Keil, A., Gruber, T., Müller, M. M., Moratti, S., Stolarova, M., Bradley, M. M., & Lang, P. J. (2003). Early modulation of visual perception by emotional arousal: Evidence from steady-state visual evoked brain potentials. *Cognitive, Affective, & Behavioral Neuroscience*, *3*(3), 195–206.

Kim, D., Ling, S., & Watanabe, T. (2015). Dual mechanisms governing reward-driven perceptual learning. *F1000Research*, *4*, 764, doi:10.12688/f1000research.6853.1.

Kim, D., Seitz, A. R., & Watanabe, T. (2015). Visual perceptual learning by operant conditioning training follows rules of contingency. *Visual Cognition*, *23*(1–2), 147–160, doi:10.1080/13506285.2015.1015663.

Lee, S. H., & Dan, Y. (2012). Neuromodulation of brain states. *Neuron*, *76*(1), 209–222.

Lee, T.-H., Baek, J., Lu, Z.-L., & Mather, M. (2014). How arousal modulates the visual contrast sensitivity function. *Emotion*, *14*(5), 978–984, doi:10.1037/a0037047.

Lee, T. H., Sakaki, M., Cheng, R., Velasco, R., & Mather, M. (2014). Emotional arousal amplifies the effects of biased competition in the brain. *Social Cognitive and Affective Neuroscience*, *9*(12), 2067–2077.

Ling, S., & Blake, R. (2012). Normalization regulates competition for visual awareness. *Neuron*, *75*(3), 531–540, doi:10.1016/j.neuron.2012.05.032.

Ling, S., & Carrasco, M. (2006a). Sustained and transient covert attention enhance the signal via different contrast response functions. *Vision Research*, *46*(8–9), 1210–1220, doi:10.1016/j.visres.2005.05.008.

Ling, S., & Carrasco, M. (2006b). When sustained attention impairs perception. *Nature Neuroscience*, *9*(10), 1243–1245.

Ling, S., Hubert-Wallander, B., & Blake, R. (2010). Detecting contrast changes in invisible patterns during binocular rivalry. *Vision Research*, *50*(23), 2421–2429.

Ling, S., Jehee, J. F., & Pestilli, F. (2015). A review of the mechanisms by which attentional feedback shapes visual selectivity. *Brain Structure and Function*, *220*(3), 1237–1250.

Ling, S., Pearson, J., & Blake, R. (2009). Dissociation of neural mechanisms underlying orientation processing in humans. *Current Biology*, *19*(17), 1458–1462.

Ling, S., Pratte, M. S., & Tong, F. (2015). Attention alters orientation processing in the human lateral geniculate nucleus. *Nature Neuroscience*, *18*(4), 496–498.

Lojowska, M., Gladwin, T. E., Hermans, E. J., & Roelofs, K. (2015). Freezing promotes perception of coarse visual features. *Journal of Experimental Psychology: General*, *144*(6), 1080–1088.

Mather, M., Clewett, D., Sakaki, M., & Harley, C. W. (2015). Norepinephrine ignites local hot spots of neuronal excitation: How arousal amplifies selectivity in perception and memory. *Behavioral and Brain Sciences*, *39*, 1–100, http://doi.org/10.1017/S0140535X15000667.

McGinley, M. J., Vinck, M., Reimer, J., Batista-Brito, R., Zagha, E., Cadwell, C. R., … McCormick, D. A. (2015). Waking state: Rapid variations modulate neural and behavioral responses. *Neuron*, *87*(6), 1143–1161.

Moradi, F., & Heeger, D. J. (2009). Inter-ocular contrast normalization in human visual cortex. *Journal of Vision*, *9*(3):13, 1–22, doi:10.1167/9.3.13. [PubMed] [Article]

Moruzzi, G., & Magoun, H. W. (1949). Brain stem reticular formation and activation of the EEG. *Electroencephalography and Clinical Neurophysiology*, *1*(4), 455–473.

Naka, K. I., & Rushton, W. A. (1966). S-potentials from colour units in the retina of fish (*Cyprinidae*). *The Journal of Physiology*, *185*(3), 536–555.

National Highway Traffic Safety Administration, U.S. Department of Transportation. (2011). Previous data. Available at https://crashstats.nhtsa.dot.gov/Api/Public/ViewPublication/811449

Niell, C. M., & Stryker, M. P. (2010). Modulation of visual responses by behavioral state in mouse visual cortex. *Neuron*, *65*(4), 472–479, doi:10.1016/j.neuron.2010.01.033.

O'Doherty, J. P., Dayan, P., Friston, K., Critchley, H., & Dolan, R. J. (2003). Temporal difference models and reward-related learning in the human brain. *Neuron*, *38*(2), 329–337.

O'Doherty, J. P., Dayan, P., Schultz, J., Deichmann, R., Friston, K., & Dolan, R. J. (2004). Dissociable roles of ventral and dorsal striatum in instrumental conditioning. *Science*, *304*(5669), 452–454, http://doi.org/10.1126/science.1094285.

O'Doherty, J. P., Deichmann, R., Critchley, H. D., & Dolan, R. J. (2002). Neural responses during anticipation of a primary taste reward. *Neuron*, *33*(5), 815–826.

Ohzawa, I., Sclar, G., & Freeman, R. D. (1982). Contrast gain control in the cat visual cortex. *Nature*, *298*(5871), 266–268.

Parker, A. J., & Newsome, W. T. (1998) Sense and the single neuron: Probing the physiology of perception. *Annual Reviews in Neuroscience*, *21*, 227–277.

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: transforming numbers into movies. *Spatial Vision*, *10*(4), 437–442.

Pestilli, F., Ling, S., & Carrasco, M. (2009). A population-coding model of attention's influence on contrast response: Estimating neural effects from psychophysical data. *Vision Research*, *49*(10), 1144–1153, doi:10.1016/j.visres.2008.09.018.

Phelps, E. A., Ling, S., & Carrasco, M. (2006). Emotion facilitates perception and potentiates the perceptual benefits of attention. *Psychological Science*, *17*(4), 292–299.

Polack, P. O., Friedman, J., & Golshani, P. (2013). Cellular mechanisms of brain state-dependent gain modulation in visual cortex. *Nature Neuroscience*, *16*(9), 1331–1339.

Pratte, M. S., Ling, S., Swisher, J. D., & Tong, F. (2013). How attention extracts objects from noise. *Journal of Neurophysiology*, *110*(6), 1346–1356.

Reimer, J., Froudarakis, E., Cadwell, C. R., Yatsenko, D., Denfield, G. H., & Tolias, A. S. (2014). Pupil fluctuations track fast switching of cortical states during quiet wakefulness. *Neuron*, *84*(2), 355–362.

Reynolds, J. H., & Chelazzi, L. (2004). Attentional modulation of visual processing. *Annual Reviews in Neuroscience*, *27*, 611–647.

Reynolds, J. H., & Heeger, D. J. (2009). The normalization model of attention. *Neuron*, *61*(2), 168–185, doi:10.1016/j.neuron.2009.01.002.

Sara, S. J. (2009). The locus coeruleus and noradrenergic modulation of cognition. *Nature Reviews Neuroscience*, *10*(3), 211–223, doi:10.1038/nrn2573.

Schneider, K. A., & Kastner, S. (2009). Effects of sustained spatial attention in the human lateral geniculate nucleus and superior colliculus. *The Journal of Neuroscience*, *29*(6), 1784–1795.

Seitz, A. R., Kim, D., & Watanabe, T. (2009). Rewards evoke learning of unconsciously processed visual stimuli in adult humans. *Neuron*, *61*(5), 700–707, doi:10.1016/j.neuron.2009.01.016.

Shadlen, M. N., Britten, K. H., Newsome, W. T., & Movshon, J. A. (1996). A computational analysis of the relationship between neuronal and behavioral responses to visual motion. *The Journal of Neuroscience*, *16*(4), 1486–1510.

Song, I., & Keil, A. (2014). Differential classical conditioning selectively heightens response gain of neural population activity in human visual cortex. *Psychophysiology*, *51*(11), 1185–1194.

Valentino, R. J., & Van Bockstaele, E. (2008). Convergent regulation of locus coeruleus activity as an adaptive response to stress. *European Journal of Pharmacology*, *583*(2–3), 194–203, doi:10.1016/j.ejphar.2007.11.062.

Vinck, M., Batista-Brito, R., Knoblich, U., & Cardin, J. A. (2015). Arousal and locomotion make distinct contributions to cortical activity patterns and visual encoding. *Neuron*, *86*(3), 740–754.

Wang, C.-A., & Munoz, D. P. (2015). A circuit for pupil orienting responses: Implications for cognitive modulation of pupil size. *Current Opinion in Neurobiology*, *33*, 134–140, doi:10.1016/j.conb.2015.03.018.

Watson, A. B., & Pelli, D. G. (1983). QUEST: A Bayesian adaptive psychometric method. *Perception & Psychophysics*, *33*(2), 113–120.

Wierda, S. M., van Rijn, H., Taatgen, N. A., & Martens, S. (2012). Pupil dilation deconvolution reveals the dynamics of attention at high temporal resolution. *Proceedings of the National Academy of Sciences, USA*, *109*(22), 8456–8460.

Woods, A. J., Philbeck, J. W., & Wirtz, P. (2013). Hyper-arousal decreases human visual thresholds. *PLoS One*, *8*(4), e61415.

Zhuang, J., Bereshpolova, Y., Stoelzel, C. R., Huff, J. M., Hei, X., Alonso, J. M., & Swadlow, H. A. (2014). Brain state effects on layer 4 of the awake visual cortex. *The Journal of Neuroscience*, *34*(11), 3888–3900, doi:10.1523/JNEUROSCI.4969-13.2014.