



Contrast discrimination under task-induced mental load

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ABSTRACT

Task-induced mental load can potentially degrade visual performance, which could be important during tasks such as driving. In the natural world, most objects have visual contrasts that are supra-threshold, and so the ability to reliably distinguish the borders between these objects is related to contrast discrimination, rather than absolute contrast detection performance. This study investigated the effects of auditory task-induced mental load on contrast discrimination threshold across several spatial frequencies. Binocular contrast discrimination thresholds were measured in 14 participants at spatial frequencies of 0.25, 1, 4, 8, 14 cpd across pedestal contrast levels of 10, 16, 24, 38 and 60%. The task was repeated with an auditory 0-back task and 2-back task to impose a mental load, the magnitude of which was measured through subjective ratings and heart rate recording. A concurrent 2-back task significantly increased contrast discrimination thresholds across all spatial frequencies when compared to both the baseline and 0-back conditions. There was no significant effect of mental load on the slope of the Threshold vs Contrast function once potential ceiling effects in our staircase procedure were removed. We conclude that mental load induced by concurrent cognitive tasks can increase contrast discrimination thresholds. When evaluating an individuals' performance under natural-world condition such as driving, the effects of task-induced mental load on contrast discrimination thresholds should be considered.

1. Introduction

Contrast discrimination thresholds are a measure of the just-detectable increment in stimulus contrast above some baseline contrast (Legge & Foley, 1983). In natural world conditions, most objects have visual contrasts that are supra-threshold, and so our ability to reliably distinguish the borders between these objects is related to our contrast discrimination – rather than our absolute contrast detection – performance. Previous work has measured contrast discrimination thresholds using sinewave grating stimuli, and has found the slope of the Threshold versus Contrast (TvC) curve for supra threshold contrast was approximately 0.9 over a range of spatial frequencies (Bradley & Ohzawa, 1986). The slope of the TvC was reduced at very low spatial frequencies (0.5 cpd), however.

Contrast discrimination performance is commonly investigated in isolation in a laboratory setting. However, in the natural world, our ability to discriminate contrasts occurs in the presence of a variety of potential distractors that may increase mental load. Mental load has been defined in relation to the demands imposed by tasks on an individual's limited information-processing resources (Eggemeier, 1988). Measuring an individual's function under mental load can better evaluate an individual's ability under natural world conditions (Recarte &

Nunes, 2003). The effects of mental load on visual performance may be of particular importance during tasks requiring good vision in order to maintain safety. For example, whilst driving under poor-lighting conditions, the additional mental load imposed by the concurrent use of a cell phone could be significant.

The effects of internal states, such as attention and arousal, on contrast sensitivity (Cameron, Tai, & Carrasco, 2002; Carrasco, Penpeci-Talgar, & Eckstein, 2000; Lee, Baek, Lu, & Mather, 2014; Phelps, Ling, & Carrasco, 2006) and contrast discrimination (Huang & Dobkins, 2005) have been investigated previously. Increasing the amount of attention allocated to a visual task can enhance performance on that task, with Carrasco et al. (2000) finding sensitivity enhancement of between ~ 0.05 and 0.1 log units over a broad range of spatial frequencies (Carrasco et al., 2000). In such studies, attention typically is modulated by visual means – e.g. pre-cueing the location of the visual target (Cameron et al., 2002; Carrasco et al., 2000) or by drawing attention away from the stimuli by use of a concurrent visual task presented elsewhere (Huang & Dobkins, 2005; Morrone, Denti, & Spinelli, 2004). Also, presenting emotional stimuli has resulted in contrast sensitivity being increased at low spatial frequencies (Lee et al., 2014) and decreased at middle spatial frequencies (~ 2 – 7 c/deg) (Lee et al., 2014). Sensitivity shifts are small, however, with Lee et al. (2014) finding

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shifts of approximately 0.09 and 0.05 log units at low and middle spatial frequencies, respectively. This interaction of spatial frequency with the induced changes in contrast sensitivity has been explained in terms of different effects of the amygdala and emotion on neural channels; i.e. potentiating magnocellular channels and suppressing parvocellular channels (Bocanegra & Zeelenberg, 2009; Nicol, Perrotta, Calciuri, & Wachowiak, 2013).

Inducing mental load by performing addition problems delivered through a hands-free phone has been shown to adversely affect driving (Strayer & Johnston, 2001; Strayer, Drews, & Johnston, 2003). As driving involves many supra-threshold visual tasks, this raises the possibility that increased mental load causes a measurable alteration in visual function, particularly contrast discrimination. However, the influence on contrast discrimination of a concurrent, non-visual secondary task that induces mental load is currently unknown. The slopes of contrast discrimination functions measured without a concurrent task do not appear to be spatial-frequency-dependent (Bradley & Ohzawa, 1986), although it may be that the effect of mental load on contrast discrimination may show a spatial frequency dependency as seen previously in contrast detection studies (Bocanegra & Zeelenberg, 2009; Lee et al., 2014; Phelps et al., 2006), particularly if the effects of mental load are, in part, mediated by the amygdala. Therefore, in this study we investigate whether performance on a contrast discrimination task at several spatial frequencies can be affected by increasing mental load through a simultaneously performed, auditory n-back task.

2. Material and methods

2.1. Participants

Fourteen right-handed participants were recruited from optometry students of the local University of Medical Sciences. All participants had normal ocular health, as assessed by ophthalmoscopy and slit-lamp biomicroscopy, reported good general health, and were free from taking medicine at the time of the experiment. Best-corrected visual acuity was equal to or better than 6/6 in each eye. This study complied with the Declaration of Helsinki and was approved by the local Human Research Ethics Committee. All the participants signed a written consent form.

2.2. Procedure

Contrast discrimination stimuli were generated using Psychtoolbox (version 3) (Brainard & Vision, 1997) in MATLAB R2012a (The Mathworks, Natick, MA) and were presented on a 22-inch (nominal diagonal measure) black and a white cathode ray tube monitor with resolution of 1800×1440 pixels at a frame rate of 75 Hz (Iiyama/Vision Master Pro 513, North America) whose visible portion subtended 11.3×8.4 degrees at the 200 cm viewing distance. Our system provided 8-bit control of luminance. Luminance calibration of the monitor, and the verification of contrast levels, was performed with a TES 137 luminance meter (ES Electrical Electronic Corp. Taiwan). The monitor was warmed up for a minimum of 30 min before each experimental session to reduce luminance variations.

The stimuli consisted of Gabor patches with a standard deviation of 1.14 degrees, and a mean luminance of 52 cd/m^2 . Patches were tilted randomly either 45° towards the right or left. Patches were presented at the centre of a screen, and a small (0.1°) red fixation dot was superimposed to aid fixation.

We determined contrast discrimination thresholds using a two-interval forced choice (2IFC) staircase procedure. On each trial, gratings were presented for 500 ms, with an inter-stimulus interval of 500 ms, followed by a response time of 1500 ms (Fig. 1). One interval, selected at random, contained the pedestal (background) contrast whilst the other contained the pedestal + test contrast. Subjects were required to determine the interval with higher contrast level by pressing one of two arrow keys on a computer keyboard, using the index or middle finger of

their dominant hand. At the start of the staircase, the test contrast was 0.2 log unit higher than the pedestal contrast, with two successive correct responses leading to a 0.05 log unit decrease in contrast of the test contrast, while one incorrect response led to a 0.05 log unit increase. The maximum Michelson contrast permitted in the staircase algorithm was 100%. If a participant failed to respond within the 1500 ms response window, the same contrast was presented again but with the interval order re-randomized. A visual mask (a random dot texture, of similar contrast to the pedestal) was presented for 500 ms between each grating in a trial in order to obscure any afterimages of the first grating. For each spatial frequency and pedestal contrast, 40 trials were performed, with threshold given as the mean of the staircase reversals after the first 5 trials were excluded. A single spatial frequency and pedestal contrast was tested in each run, and a break of 15 min was provided to all participants after the first 10 runs in the 25 run session. Participants were also advised that they could take additional rest breaks during testing, as required.

Binocular contrast discrimination was measured at low (0.25 & 1), medium (4) and high (8 & 14 cpd) spatial frequencies across various pedestal contrast levels (10%, 16%, 24%, 38% & 60%). Test order was randomized for each participant.

To evaluate the effect of mental load on contrast discrimination, the task was repeated with an auditory n-back task generated within the main contrast discrimination programme. In the n-back test, participants were required to listen to a sequence of letters (drawn from 20 English letters) and to manually respond when the current letter matched the one from n steps earlier in the sequence. The n factor can be used to set the difficulty level of the task (Pelegri et al., 2015), with $n = 2$ selected for the current study. Because the added “noise” of having to perform the n-back task concurrently could itself change contrast discrimination threshold, irrespective of mental load, we also performed a 0-back task (i.e. a substantially easier mental load than the 2-back task) to control for this noise effect. For the 2-back task, participants were required to use their index fingers of their non-dominant hands to register a match by pressing the enter key of a keyboard separate to that used for the contrast discrimination task, and for 0-back they pressed the same enter key when they heard the letter X (Gajewski, Hanisch, Falkenstein, Thönes, & Wascher, 2018). Each letter was presented within a 500 ms window, with an inter-stimulus interval of 1000 ms. The task was synchronised with the contrast discrimination task and was started 500 ms after starting the contrast discrimination task so that letters were presented both concurrently with the first interval in the contrast discrimination task, and in the middle of the contrast discrimination response window (see Fig. 1). The frequency that participants needed to manually respond in both the 0- and 2-back tasks was matched, being 25% of letter presentations. For the 2-back task, a separate practice run was performed before commencing data collection. The order of task condition (no auditory task, 0-back, and n-back) was counterbalanced. Each task condition was performed on a separate day.

We assessed the level of mental load for each task condition using a concurrent heart rate recording (A300 heart rate monitor with a chest strap, Polar Electro Oy), and a retrospective measurement (Subjective Rating Scale of Mental Effort (RSME) provided to the participants immediately after each task). The RSME has nine descriptive labels ranging from “absolutely no effort” to “extreme effort” that converts to a numerical scale from 0 to 150 (Widyanti, Johnson, & de Waard, 2013). Participants were requested to mark a corresponding label with the amount of mental effort used to complete the task.

2.3. Statistical analysis

For our analyses of contrast discrimination thresholds, we used SPSS version 15 (Chicago, SPSS Inc) and plotted figures with GraphPad Prism version 6.07 for Windows (GraphPad software. Inc). Multi factorial, repeated-measures ANOVA testing was used to investigate any potential

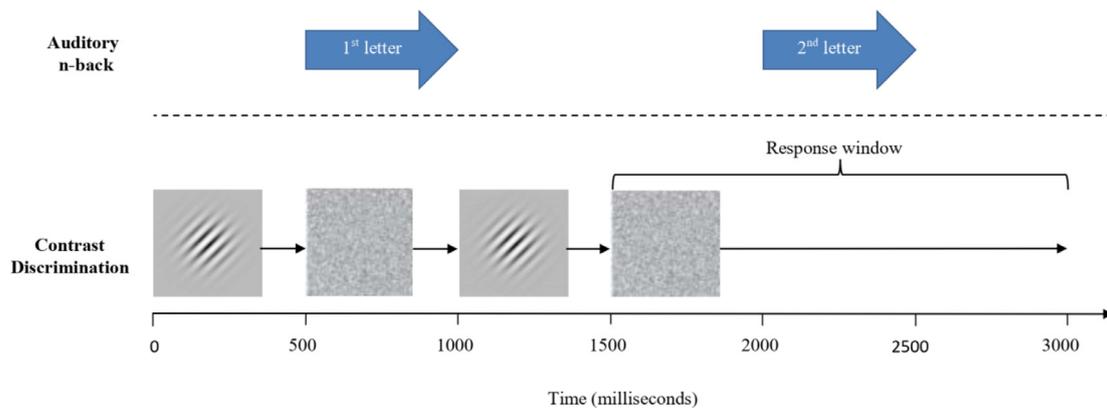


Fig. 1. A schematic presentation of the contrast discrimination task with auditory n-back task. Responses in the n-back task could occur at any time, except during the 500 ms when a letter was being presented.

effect of task condition, spatial frequency, and pedestal contrast level on contrast discrimination thresholds. Greenhouse-Geisser corrections were used when the assumption of sphericity was violated. Results were reported as means with the 95% confidence interval of differences obtained from pair wise comparisons with Bonferroni-correction. We used linear regression (Microsoft Excel for Mac, Version 16.16.3, Redmond, WA) to determine the slope of the log contrast discrimination vs log pedestal contrast function for each spatial frequency and task condition, with subsequent statistical analysis of these data performed in SPSS version 15 (Chicago, SPSS Inc). We used log contrast discrimination thresholds for all analyses.

3. Results

Fourteen participants (mean age \pm SD: 22.2 ± 1.1 years) participated in the study. Two participants were excluded from our analysis because of poor performance on the 2-back task ($< 75\%$ accuracy). A Kolmogorov-Smirnov test showed a normal distribution for the remaining data ($p > 0.05$).

Task condition significantly affected the subjective rating score of mental effort ($P = 0.001$) (Fig. 2a), with our 2-back task showing significantly greater effort than baseline (RMSE score difference: 32.66; 95% CI: 10.52, 54.81; $P = 0.005$) or 0-back conditions (25.66; 95% CI: 6.23, 45.10; $P = 0.01$). Subjectively rated mental effort was not significantly different between baseline and 0-back conditions (7.00; 95% CI: $-7.10, 21.10$; $P = 0.568$). A repeated measures ANOVA showed no

significant difference in average heart rate between the baseline and n-back task conditions ($P = 0.336$; Fig. 2b).

Fig. 3 shows the average TvC functions measured across task conditions and spatial frequencies. Average contrast discrimination thresholds were significantly increased during the 2-back task when compared to the baseline and 0-back condition (2-back with baseline: 0.345; 95% CI: 0.218, 0.472; $P < 0.001$, 2-back with 0-back: 0.322; 95% CI: 0.177, 0.468; $P < 0.001$). There was no significant interaction between mental load and spatial frequency ($P = 0.642$).

We also determined TvC functions for each participant and calculated their slopes, using linear regression, for each spatial frequency and task condition. The average of the TvC slopes are reported in Table 1. A repeated measures ANOVA found a significant effect of mental load ($P = 0.006$) and spatial frequency ($P < 0.001$) on TvC slope, but no significant interaction between mental load and spatial frequency ($P = 0.191$). A pairwise comparison showed significant reduction in the slope of the TvC functions with mental load (2-back with baseline: -0.152 ; 95% CI: $-0.268, -0.035$; $P = 0.011$, 0-back with baseline: -0.086 ; 95% CI: $-0.208, 0.036$; $P = 0.217$). To assess the effect of our n-back task on lapsing probabilities, we fitted cumulative Gaussian psychometric functions (probability correct as a function of log contrast increment) to each observer's staircase data using a maximum likelihood procedure (Treutwein & Strasburger, 1999). We optimized fits using the Solver function of Microsoft Excel, and took the median parameters of three fits starting from different initial parameters. Minimum slope and lapsing rate were set to 0.01 and 0.001 respectively, the guessing rate fixed at 0.5, and trials where the staircase presented an increment of 0 were ignored. Lapsing rates converged to the limit of 0.01 for all participants and all conditions barring a single case (one participant: lapsing rate = 0.14 for the zero-back condition), indicating there was no increase in lapsing rate under our n-back condition. However, these data only include those trials where a response was made. We therefore analyzed the number of missed trials in the three conditions for all pedestal contrasts at a representative spatial frequency (4 cpd), using a repeated measures ANOVA. The mean number of missed trials in all pedestal contrast levels was 0.9 ± 1.94 , 0.86 ± 2.25 and 4.41 ± 2.04 for the baseline, 0-back and n-back conditions, respectively. There was a significant effect of task condition on the number of missed trials ($P = 0.008$), with pair-wise comparison with Bonferroni-corrected testing revealing an increase in missed trials in the 2-back condition relative to baseline (3.967; 95%CI: 0.415, 7.51; $P = 0.028$) but not relative to the zero-back condition ($P = 0.095$). The baseline and zero-back conditions did not differ significantly ($P > 0.99$). There was no significant effect of pedestal contrast level on the number of missed trials ($P = 0.817$), and no significant interaction between the effects of pedestal contrast and test condition ($P = 0.518$), meaning that there was a similar number of missed trials at all pedestal contrast levels for each task condition.

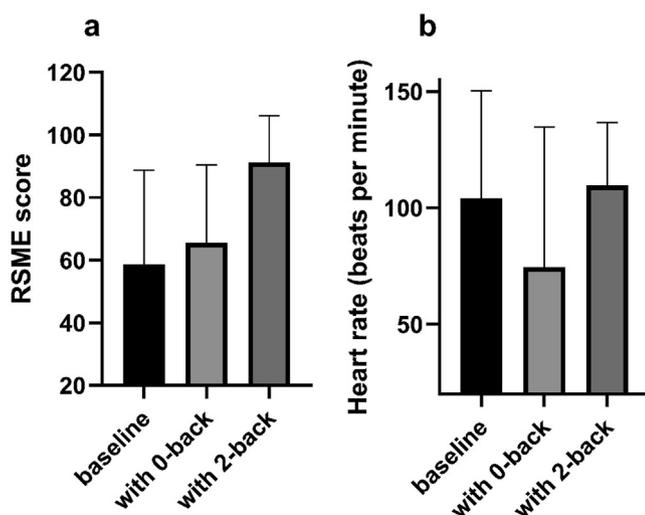


Fig. 2. The mean and SD of Subjective Rating Scale of Mental Effort RSME score (left hand panel) and heart rate (right hand panel) for the three task conditions.

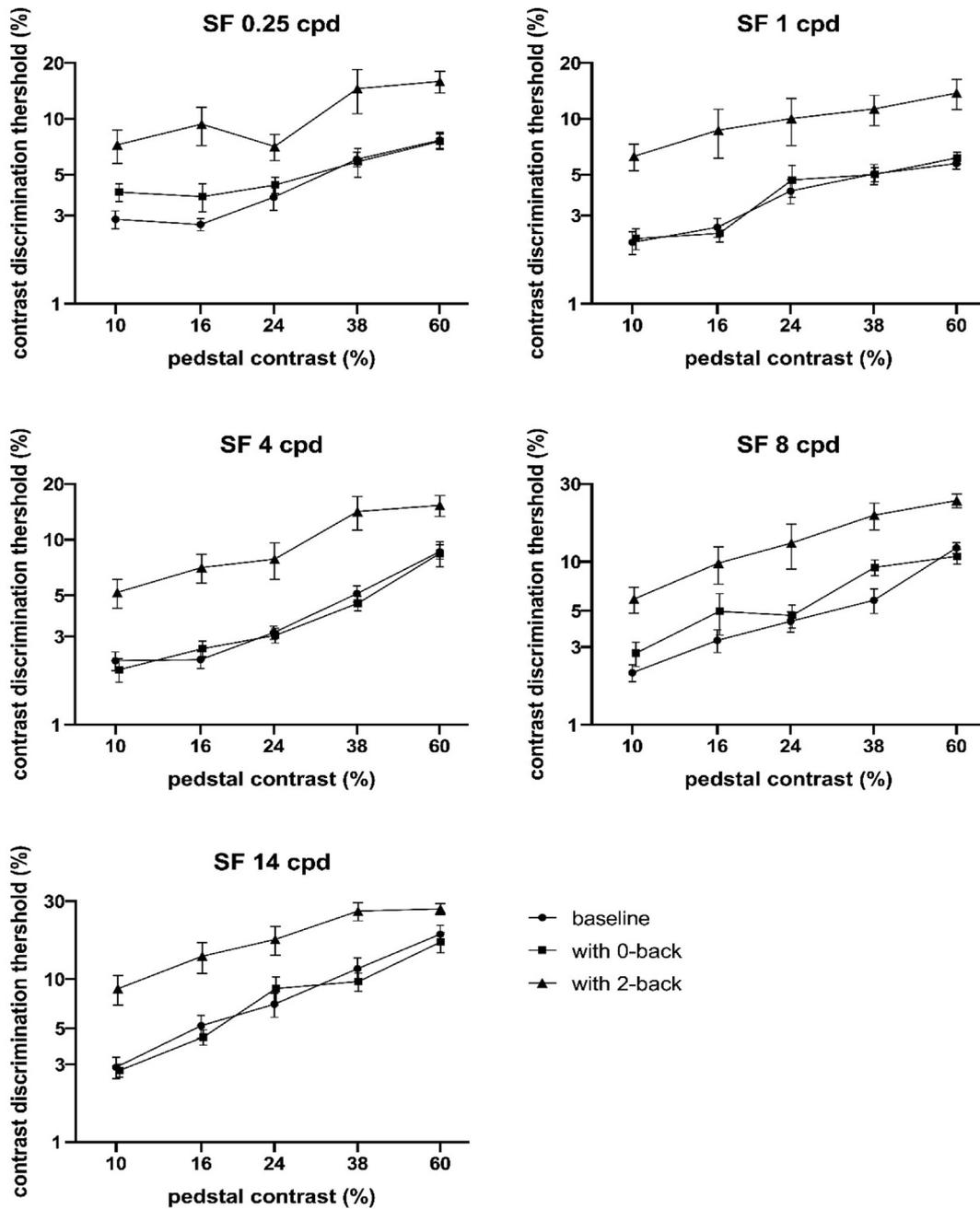


Fig. 3. Contrast discrimination vs. pedestal contrast for various spatial frequencies in the three task conditions. Error bars indicate standard errors. A small horizontal displacement has been introduced in the x-axis, to allow the visualization of closely spaced data points.

It is possible that our limiting of our staircase procedures to a ceiling of 100% contrast could cause a flattening of TvC slope in our 2-back condition if staircases for high pedestal contrasts hit this limit more commonly than under baseline or 0-back conditions. This could

artificially lower measured thresholds for high pedestals, thereby flattening TvC slope. We therefore evaluated the number of times that the 100% contrast limit was reached during staircases for each participant. The 100% contrast limit was only ever reached for spatial frequencies

Table 1

The mean ± standard error of the individual slopes of the TvC functions. Values in parentheses (8 & 14 cpd) are slopes determined from the four lowest pedestal contrasts only, so as to avoid any contrast ceiling effects in the staircase procedure.

Spatial frequencies	Baseline condition	With 0-back task condition	With 2-back task condition
0.25 cpd	0.630 ± 0.06	0.399 ± 0.06	0.501 ± 0.08
1 cpd	0.617 ± 0.05	0.641 ± 0.06	0.461 ± 0.05
4 cpd	0.811 ± 0.07	0.789 ± 0.10	0.673 ± 0.07
8 cpd	0.943 ± 0.08 (0.740 ± 0.12)	0.812 ± 0.08 (0.857 ± 0.09)	0.878 ± 0.09 (0.869 ± 0.13)
14 cpd	1.029 ± 0.10 (1.024 ± 0.12)	0.959 ± 0.07 (0.949 ± 0.12)	0.760 ± 0.12 (0.890 ± 0.14)

of 8 and 14 cpd at a pedestal contrast of 60% (for SF 14 cpd in the three task conditions for 9 participants, and for SF 8 cpd only in the n-back task condition for 6 participants). We therefore took a conservative approach and re-determined individual's TvC slopes for spatial frequencies 8 and 14 for each task condition using only the four lowest pedestal contrast (i.e. with the 60% contrast pedestal excluded), and then re-ran our analysis of the effect of mental load on TvC slope (using all spatial frequencies) outlined above. The effect of mental load on slope of TvC reported above was no longer significant ($P = 0.498$). The revised slopes for the 8 and 14 cpd conditions are given in parentheses in Table 1.

4. Discussion

Our results showed that task-induced mental load had a significant negative effect on contrast discrimination thresholds. Once potential ceiling effects in our staircase procedure were removed, there was no influence of mental load on TvC slope, indicating that mental load impaired discrimination equally for less salient stimuli and for highly salient stimuli.

Multiple cognitive steps – such as attention, working memory and decision-making – are involved in n-back tasks (Pelegriña et al., 2015). Previous work has shown that the mechanisms underlying such cognitive steps have a limited capacity (Marois & Ivanoff, 2005; Moray, 1967), and so performing a concurrent n-back, or other demanding, auditory task could potentially overwhelm this capacity and so cause errors in information processing and reduce primary task performance. Indeed, Richard et al. (2002) showed decreased visual search performance when participants had to concurrently perform an auditory task (Richard et al., 2002). Our results showed that an auditory 2-back task can impose high mental load, as indicated by increased RSME scores for our participants (Fig. 2a).

We showed that there was no significant interaction between mental load and pedestal contrast, as indicated by the fact that TvC slope did not change under mental load conditions. Previous studies evaluated the effect of attention using a dual visual task to measure contrast discrimination under full and poor attention conditions (Huang & Dobkins, 2005; Morrone et al., 2004). Attention was either directed to the peripherally presented contrast stimuli (full attention) or was directed away from the stimuli by use of a concurrent, centrally presented visual task (poor attention). Their results showed contrast discrimination thresholds increased when attention was poor, which is in keeping with our current findings regarding the effects of increased mental load. Huang and Dobkins (2005), using a 2 cpd stimulus, found that there was an influence of pedestal contrast, with the effects of attention being greater for lower pedestals. This result is dissimilar to the pedestal contrast independent effect of mental load that we describe here (i.e. the lack of a TvC slope change), once the possibility of ceiling effects has been removed.

Our use of fixed pedestal contrasts meant that these pedestals would be expected to fall either closer to or further from the dip in the TvC function as spatial frequency (and, therefore, contrast thresholds) altered. We were unable to measure contrast discrimination at very low pedestal contrast levels to ascertain the position of the TvC dip, because of the limited bit depth of our display (8-bit resolution and 256 grey levels). Our lowest contrast (10%) was reasonably high, however, and would be expected to fall comfortably on the rising portion of our TvC functions for the spatial frequencies we investigated, based on previous studies (Bradley & Ohzawa, 1986; Ling, Hubert-Wallander, & Blake 2010; Watanabe, Paik, & Blake, 2004). The shape of the TvC function can be used to infer the underlying contrast-response function that gives the relationship between stimulus contrast and the induced neural response. In particular, it is possible to distinguish changes in contrast gain from response gain by using data from a TvC to model contrast-response functions. A change in contrast gain alters the effective contrast of the stimulus, resulting in an identically shaped contrast-

response function that is horizontally translated on a log-contrast axis (Sclar, Lennie, & DePriest, 1989). Conversely, a change in response gain alters the shape of the contrast-response function (Di Russo, Spinelli, & Morrone, 2001; Ling et al., 2010). Our TvC functions – designed to be determined for a range of conditions within a single session – are sparsely sampled compared to previous work, and so are not well suited to formal modelling of the contrast-response function, however. For example, the model of Boynton, Demb, Glover, and Heeger (1999) contains four free parameters, and so would require TvC curves generated from at least five contrast pedestals to adequately constrain it, which is more than the four pedestal contrasts we have for our high spatial frequency conditions once potential ceiling effects are removed. Whilst modelling attempts have been performed with simplified models that presume response gain changes only multiplicatively (Huang & Dobkins, 2005), other work suggests that changes in the exponents governing the acceleration of the response function are also required to explain attention-based changes to contrast discrimination (Morrone et al., 2004). A key finding in our paper is that the slope of the TvC function was not significantly altered under mental load. The supra-threshold portion of TvC functions are highly linear at a spatial frequency similar to what we investigated (Campbell & Kulikowski, 1966), making our results theoretically compatible with the horizontal translation of TvCs predicted from a pure contrast gain alteration (Ling et al., 2010). This seems highly unlikely, however, as the TvC would need to translate leftward to achieve elevated contrast discrimination thresholds at high pedestal contrasts, suggesting that increased mental load increased contrast sensitivity. More likely is that response-gain is reduced, but over a largely linear portion of the contrast-response function such that the slope of the resultant TvC remains constant.

Previous studies have shown an interaction between changes in contrast sensitivity with emotion and arousal status, with greater sensitivity increases at low spatial frequencies when compared to higher spatial frequencies (Bocanegra & Zeelenberg, 2009; Lee et al., 2014). Such interaction effects may be due to the amygdala – which is involved in internal states such as arousal (Bocanegra & Zeelenberg, 2009; Nicol et al., 2013) and working memory (Schaefer et al., 2006) and shows spatial-frequency tuned responses for processing facial emotions (Vuilleumier, Armony, Driver, & Dolan, 2003) – having different effects on magnocellular and parvocellular channels (Bocanegra & Zeelenberg, 2009; Nicol et al., 2013). However, we did not find a significant interaction between mental load and spatial frequency in our results, suggesting our elevation in contrast discrimination thresholds may differ from spatial-frequency dependent effects on sensitivities to Gabor stimuli previously attributed to the amygdala (Bocanegra & Zeelenberg, 2009). Consistent with this, we found that the 2-back task appeared to cause a generalized distraction effect, as evidenced by the significant increase in missed trials. We found no significant alteration in the number of missed trials as a function of pedestal contrast, consistent with our finding that the TvC slope did not change when concurrently performing the 2-back task, once the potential for contrast ceiling effects has been removed. A systematic decrease in slope as pedestal mask familiarity increased (Swift & Smith, 1983) is unlikely in this study, as mask familiarity would be expected to be high - even in very early trials - when the pedestal and test target have the same spatial frequency, as in our experiment. In addition, such learning also lowers thresholds (Swift & Smith, 1983), in contrast to the prominent threshold elevation we find when our n-back task was added. Finally, a learning effect on the slopes in our 2-back could only occur if these data were systematically collected later than other conditions. The sequence of each task condition was counterbalanced in our experiment, however.

5. Conclusion

Similar to effects previously seen when performing concurrent visual tasks, we found contrast discrimination thresholds increased with an auditory 2-back task. This may be due to limited information

processing resources being available when a concurrent cognitive load is present. In the natural world, the ability to distinguish the borders between visible objects is related to contrast discrimination. Performing mentally demanding concurrent tasks may lead to deleterious effects on performing such natural world contrast discrimination tasks, and so should be avoided when there are potentially high costs when the discrimination task is performed poorly, such as when driving.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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