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Impact of simulated visual impairment on the cognitive test performance of young adults

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ABSTRACT

Aims: This study investigated the effect of simulated visual impairment on the speed and accuracy of performance on a series of commonly used cognitive tests. **Methods:** Cognitive performance was assessed for 30 young, visually normal subjects (M=22.0yrs±3.1 yrs) using the Digit Symbol Substitution Test (DSST), Trail Making Test (TMT) A and B and the Stroop Colour Word Test under three visual conditions: normal vision and two levels of visually degrading filters (Vistech^{TM}) administered in a random order. Distance visual acuity and contrast sensitivity were also assessed for each filter condition. **Results:** The visual filters, which degraded contrast sensitivity to a greater extent than visual acuity, significantly increased the time to complete ($p<0.05$), but not the number of errors made, on the DSST and the TMT A and B and affected only some components of the Stroop test. **Conclusions:** Reduced contrast sensitivity had a marked effect on the speed but not the accuracy of performance on commonly used cognitive tests, even in young individuals; the implications of these findings are discussed.

BACKGROUND

It is generally well recognised that degrading an image slows or impairs the recognition and processing of that image (Harley, Dillon, & Loftus, 2004; Pashler, 1984). Indeed, the speed and processing problems of people with low vision are often explained in these terms. Generally, designers and psychologists tend to think of image clarity in terms of the size and spatial frequency of the target, such that the resolution of the image is the area of primary concern in designing clear or quickly interpretable displays (Loftus & Harley, 2005). However, an equally important consideration, which is often neglected, is the influence of stimulus contrast on cognitive performance. To date the influence of reduced stimulus contrast, representative of that encountered in individuals with true visual impairment, on cognitive performance has not been investigated.

It has been hypothesized that one effect of degrading visual input is that it makes the initial stages of visual processing more cognitively effortful. The resulting demand on cognitive resources in turn reduces those available for other higher level cognitive processes, including the encoding of new information in memory and operations such as comprehension of written information (Wingfield, Tun & McCoy, 2005). This ‘effortfulness” hypothesis was proposed as an explanation for the findings of memory studies involving auditory masking (Rabbitt, 1968), that demonstrated that a participants’ ability to recall the first half of an eight item list was negatively affected when the second half of the list was heard in the presence of masking noise. Rabbitt (1968) proposed that the increased effort associated with trying to identify digits in auditory noise deprived other cognitive processes of the resources necessary to allow elaborative encoding of the material. Similarly, reduced visual acuity and contrast sensitivity might be expected to have an analogous effect on cognitive processing.

However, stimulus contrast may also have effects selective to early levels of visual processing that are not cognitively penetrable (Pylysyn, 1999). In fact stimulus contrast manipulations are often used to selectively slow early pattern recognition processes (Pashler, 1984), presumably as a result of increasing the demands on low level visual processes.

Lindenberger, Scherer and Baltes (2001) demonstrated that reducing the visual acuity of middle-aged adults to that of older individuals using partial occlusion filters did not impair performance on a range of cognitive tests; importantly, however, the amount of contrast sensitivity degradation under these filter conditions was not recorded. However, other studies which have specifically degraded the contrast of cognitive test form material to simulate the effects of ageing have reported a significant slowing of performance on the Symbol-Digit Substitution Test (Gilmore, Spinks, & Thomas, 2006). Similarly, studies which have reduced the contrast of computer-based presentations of cognitive test material have reported_slowing (but not increased errors) in older adults on tests of perceptual matching, processing speed and associated memory (Anstey, Butterworth, Andrews, & Borzycki, 2006) and an increase in intra-individual inconsistency on a vigilance task for older but not younger adults (MacDonald, Hultsch, & Bunce, 2006). Although these studies indicate an association between contrast sensitivity and cognitive test performance (but not visual acuity and cognition), it is not known whether these effects would be obtained under levels of visual degradation more representative of early visual impairment. For instance, Gilmore et al., (2006) used image processing techniques to simulate the degradation of a visual stimulus comparable to that produced by the visual system of an 80 year old observer. One limitation of image processing and other techniques for simulating visual degradation is that they cannot simulate the effects of intraocular light scatter and glare sensitivity that are also associated with eye diseases and that can significantly impact on visual performance.

The aim of this study was to determine whether visual filters, which have been shown to reduce contrast sensitivity to a greater extent than visual acuity and, are representative of mild to moderate cataracts (Elliott et al 1996), would affect the speed and accuracy of performance on a battery of commonly used cognitive tests. These cognitive tests were selected to be visually complex and to have a timed component to better capture any effects of visual degradation on both speed and accuracy of cognitive test performance. The use of a young visually normal group who were free of lens opacities was considered useful as a first step in the investigation of this relationship because it avoided combining naturally occurring lens opacities with the filters, as young eyes provide little variability in lenticular function. If visual function *per se* influences cognition and not interactions with other age-related factors, impairment should be evident in this group also.

METHODS

Participants

Thirty young, visually normal adults (mean age 22.00 yrs ± 3.1 yrs; age range 18 – 33 years) were recruited from first year Optometry students and their University colleagues to participate in this study. The sample consisted of 14 males and 16 females who were in good general health, had no self-reported neurological illness or cognitive impairment and were free of ocular disease. All participants had distance visual acuity equal to or better than 6/6 (20/20).

The study was conducted in accordance with the requirements of the Queensland University of Technology Human Research Ethics Committee and followed the tenets of the Declaration of Helsinki. All participants were given a full explanation of the experimental procedures and written informed consent was obtained, with the option to withdraw from the study at any time.

Simulated Visual Impairment

The visual degradation resulting from age-related lens changes and cataracts was simulated using a series of Vistech^{TM} cataract simulation filters (Vistech Consultants Inc., Dayton, OH). Elliott, Bullimore, Patla and Whittaker (1996) found that the Vistech^{TM} simulation goggles produce wide-angle light scatter (light scatter between 5 and 20 degrees) with a similar angular distribution to normal and cataractous eyes. The filters were found to have a greater effect on contrast sensitivity than visual acuity and increase intraocular light scatter and glare sensitivity like real cataracts, which is the opposite of refractive blur which has a greater effect on visual acuity (Bradley, Hook, & Haeseker, 1991). Their studies demonstrated that one filter simulates the effect of mild cataracts (Elliott et al., 1996). We also wished to simulate the effects of moderate cataracts. In our previous studies we found that patients with moderate bilateral cataracts who were still driving had Pelli-Robson Letter CS scores of 1.43 ± 0.16 providing a lower 95% confidence limit of 1.12 log units (Wood & Carberry, 2006). In pilot studies we found that two filters used together reduced Pelli-Robson Letter CS to approximately these levels and this was used as our moderate cataract simulation.

The cataract simulation goggles were used as a baseline condition with no filter in place, condition one with a single Vistech filter, and condition two represented by two Vistech filters mounted together.

Vision Assessment

All testing was undertaken with the participants' optimal refractive correction appropriate for the working distance together with the cataract simulation goggles. Distance visual acuity and letter contrast sensitivity were measured binocularly for each participant for each of the three visual conditions (no filter, one filter and two filters combined); the order of testing was randomised.

Static Visual Acuity.

Visual acuity was tested using a high contrast (90%) Bailey-Lovie (logMAR) chart at a working distance of 3 m under the recommended illumination conditions. LogMAR charts, such as the Bailey-Lovie chart have become the standard for clinical research and have many advantages over traditional Snellen charts, including a logarithmic progression of letter sizes and letter and line spacing, equal numbers of letters per line and letters of similar legibility. A visual acuity measurement of 6/6 (20/20) in traditional Snellen notation corresponds to a minimum angle of resolution (MAR) of 1 minute of arc and a logMAR of 0.00. Participants were instructed to read the letters from left to right on the chart and were encouraged to guess letters even when unsure. Visual acuity was scored on a letter by letter basis, where each letter correctly identified represented a score of 0.02 log units.

Pelli-Robson Letter Contrast Sensitivity.

Letter contrast sensitivity was measured using the Pelli-Robson chart under the recommended viewing conditions (Pelli, Robson & Wilkins, 1988). This chart uses large letters which correspond to a spatial frequency of approximately one cycle/degree at a testing distance of one metre. The letters are arranged in groups of three of the same contrast (triplets), each successive triplet decreases in contrast by a factor of 0.15 log units. Participants were asked to read as far down the chart as they could and encouraged to look at a line of letters and guess the letter when they were unsure; each letter reported correctly was scored as 0.05 log units.

Cognitive Tests

The three cognitive tests included in this study were selected because they are commonly used and visually based and therefore more likely to be sensitive to the effects of visual impairment.

Digit Symbol Substitution Test

The Digit Symbol Substitution Test (DSST) (Wechsler, 1981) is a measure of general information processing speed (Spreen & Strauss, 1998) and has been widely used in studies of cognitive ageing. The pen and paper version of the test was used, where the test stimulus is printed on white A4 paper and includes a key at the top of the page which specifies the particular symbols that correspond to each numerical digit from 1-9. Under normal room illumination and table seating, participants were instructed to write the correct symbol corresponding to the random array of digits as quickly and accurately as possible according to the coding key. The DSST score was recorded as the number of correct symbols drawn in 90 sec and the number of errors made. Both speed and accuracy were equally emphasized in the instructions to ensure consistency (Wong & Gilpin, 1991). Participants were specifically instructed to use their non-writing hand as a page support to prevent them pointing to symbols on the key.

Trail Making Tests A and B

The pencil and paper version of the Trail Making Test from the Halstead-Reitan Neuropsychology Test Battery was used (Spreen & Strauss, 1998) which assesses motor speed, visual attention, mental flexibility and motor function (Lezak, 1995). This is a timed task consisting of two sub-tests: Parts A and B which are both presented on white paper. Part A consists of 25 randomly positioned encircled numbers and the subjects were required to join the numbers in chronological order, ie. 1-2-3-4. Part B consists of randomly positioned encircled numbers and letters and participants were instructed to join the numbers and letters in alternating order, ie. 1-A-2-B-3-C. Any errors made by the subjects were pointed out by the examiner immediately and corrected before continuing the sequence. A participants' score was taken as the time to complete the test to the nearest tenth of a second; the number of errors made was also recorded.

Stroop Color Word Test

The Victoria version of the Stroop Color Word Test (SCWT) (Spreen & Strauss, 1998) was used and is designed to assess an individual's ability to shift their perceptual set and is a measure of selective attention and speed of information processing. The test consists of three cards labelled part D, W and C respectively, with each consisting of six rows of four items. In Part D the subject has to name 24 coloured dots printed in red, green, yellow or blue, as quickly as possible; each colour is used six times and the four colours are arranged in a pseudorandom order within the array. In part W, the dots are replaced with a series of words (when, hard, over, and) printed in lower case N16 Times New Roman font. Participants are asked to identify the colour that the words are printed in as quickly and accurately as possible. The final part of test, part C displays colour words that are printed in incongruously coloured ink, for example the word yellow is printed in blue ink and participants are asked to name the colour of the ink in which the words are printed. The outcome measures used in this study were the mean time needed to complete the first two cards as an indication of simple speed capacity and an interference score to measure inhibition of a habitual response (reading the word). An interference score was computed by subtracting the mean score of the first and second cards from the time needed to complete the third card.

Experimental Design

The cognitive and vision tests were administered for each participant under the three visual testing conditions (zero filter, one and two Vistech filters). Each participant was given a practice run to familiarize them with the task and to ensure that they understood the task instructions, thereby reducing learning effects (Beres & Baron, 1981). The order of testing and visual conditions was balanced using a Latin square (incomplete factorial design). For each visual condition, the cognitive tests were tested prior to the vision tests to minimise the expectation that a participant might have regarding the effect of a given filter on performance.

RESULTS

Table 1 shows the group mean data for all of the vision and cognitive performance measures as a function of filter condition. Group mean contrast sensitivity with the Pelli-Robson chart was 1.98 (±0.11) log units at baseline, and was significantly reduced by the filters (*F*(2,58)=593.9, *p*<0.001, partial η^2=0.95), with all filter conditions being significantly different from one another. Visual acuity was also decreased in the presence of the filters (*F*(2,58)=267.4, *p*<0.001, partial η^2=0.90); distance visual acuity for the baseline condition was -0.09 (±0.07) which is equivalent to 6/5 (20/16) in standard Snellen notation or one line better than 6/6 or 20/20. All pairwise differences were significant (p<0.05). A two-way repeated measures ANOVA of lens condition (with 3 levels: no filter, one filter, and two filters) and visual test (with 2 levels: visual acuity and contrast sensitivity) was conducted to examine the relative effect of the filter condition on contrast sensitivity and visual acuity. To enable comparison between the measures both measures were standardized using the mean and standard deviations from the baseline (no filter) condition, and visual acuity was reversed scored, A significant two-way interaction (F(2,58)=138.14, p<0.001, partial η^2=0.83) indicated that contrast sensitivity was affected to a significantly greater extent by the filters than was visual acuity.

Importantly, the visual acuity for all filter conditions at a working distance of approximately 40 cms for all participants was calculated to be at least six lines better than the visual requirements calculated for these versions of either the DSS (logMAR 0.84), and the Trails A and B tests (logMAR 0.78). That is the printed targets used in the DSS and Trails tests were four times larger than the size required for recognition with the visual acuity levels achieved with the filters, thus it is not merely the ability to resolve the target that changed the speed of processing.

Group mean data for the cognitive tests under the three levels of visual impairment are also given in Table 1 and demonstrate that in general, cognitive test performance became worse as the number of visual filters was increased. The filters had a significant degrading effect on DSST performance, $F(2,58)=52.36$, $p<0.001$, partial $\eta^2=0.64$, and time to complete the TMT A and B, $F(2,58)=23.61$, $p<0.001$, partial $\eta^2=0.45$, and $F(2,58)=32.79$, $p<0.001$, partial $\eta^2=0.53$, respectively. For DSS performance, both the one and two filter conditions were significantly worse than the no filter condition, and were significantly different from one another. However, for both the Trails A and B tests the two filter condition was significantly worse than for either one or no filters, but there was no significant difference between the one filter and the no filter conditions. For the Stroop test only the Stroop D and W were significantly affected by the visual filters, $F(2,58)=14.15$, $p<0.001$, partial $\eta^2=0.34$ and $F(2,58)=6.33$, $p=0.003$, partial $\eta^2=0.18$ respectively, where the two filter condition was significantly worse than the no filter condition for both tests, and the two filter condition worse than that for one filter for the Stroop W. Neither the Stroop C or the Stroop Interference effect were significantly affected by the presence of visual filters $F(2,58)=2.64$, $p=0.08$, partial $\eta^2=0.09$ and $F(2,58)=1.19$, $p=0.31$, partial $\eta^2=0.04$ respectively. The visual filters had no significant effect on the error scores for any of the tests.

DISCUSSION

In this study we demonstrated that visual filters which strongly degrade contrast sensitivity but have only a modest effect on visual acuity have a marked effect on the speed but not the accuracy of cognitive performance for all of the tests included in this study with the exception of the Stroop C. This is an important finding given that the visual acuity of all participants when viewing through the filters was at least four times better than the visual resolution required to resolve the numbers and letters of both the DSS and the TMT, even for the worst filter condition (two filters together). Indeed, the filters have the greatest effect on measures of contrast sensitivity rather than visual acuity (Elliott et al., 1996), reducing letter contrast sensitivity to levels commensurate with that of patients with early cataracts for the one filter condition and that of moderate bilateral cataracts for the two filter condition (Wood & Carberry, 2006).

The finding that a reduction in contrast sensitivity impairs performance on a range of visually based cognitive tests is in accord with the findings of Skeel, Schutte, van Voorst and Nagra (2006) who reported that differences in contrast sensitivity accounted for substantial levels of unique variance in neuropsychological test performance, even when the effects of age were controlled for. In a sample of older adults, Anstey et al., (2006) also found that contrast sensitivity was associated with processing speed and that performance on measures of perceptual matching, processing speed and associative memory was slower when the visual contrast of the test stimuli was reduced. In fact, researchers have frequently employed manipulations of stimulus contrast to selectively slow pattern recognition (Pashler, 1984), presumably as a result of increasing the demands on low level visual processes. This conclusion is supported by experimental evidence demonstrating that the effects of variations in the quality of a visual stimulus are additive with the effects of other factors (e.g. number of items that need to be memorized) that influence higher level cognitive stages of processing. Recently, Harley et al., (2004) investigated the effects of reduced stimulus contrast on perception and visual memory and concluded that “contrast is a low-level variable that operates at a stage prior to that at which the system “knows” what stimulus is being analysed” (page 225). Thus reduced contrast may slow but not necessarily alter the output of low level pattern recognition processes. It is also possible that the absence of any effects on accuracy derives in part from the fact that the cognitive tests did not place a sufficient demand on higher cognitive processes, including elaborative encoding or the maintenance of information in working memory. Importantly, the effects of the filters on cognitive processing cannot merely be explained in terms of a difference in legibility of the pencil and paper tests, as performance was similarly degraded in the colour naming component of the Stroop D, which does not require reading.

While it might have been anticipated that performance on Stroop C would improve with the two filter conditions we found no such effect. Gumenik & Glass (1970) did report a reduced Stroop color interference effect when participants viewed words positioned behind a mask consisting of diagonal (45º) opaque strips. However, the effects of contrast and a visual mask are likely to differ in the degree to which they interfere with the global perception of a word. For instance, the opaque strips used by Gumenik & Glass (1970) reduce words to small visible line segments that may not form an effective Gestalt of a word. By comparison, the effects of contrast which are manifested in early stages of visual processing (Harley, Dillon, & Loftus, 2004; Li, Sweet, & Stone, 2005) appear to slow but not qualitatively alter the outcome of the word recognition process and consequently may not eliminate the Stroop effect.

Reduced contrast sensitivity might also slow performance by influencing the visual search strategies that participants employ. Gilmore et al., (2006) found that young participants who were presented with different forms of the symbol-digit substitution test that were digitally filtered, so that the spatial contrast of the forms was equivalent to the reduction in contrast produced by the visual system of an 80 year old, performed worse on the age-simulated contrast condition than in the normal condition. They proposed that in response to lower stimulus contrast, observers set a lower activation threshold for stimulus features that are shared by the object of the visual search. This, however, has the detrimental effect of increasing the number of false alarms by elements in the display that are not related to the target. Consequently, the participants adopt a slower serial search rather than a more efficient parallel search which in turn moderates their performance on timed cognitive tests. While speculative, this line of reasoning suggests another way in which contrast might affect performance.

It is yet to be determined how and under what conditions slowing would impact on working memory or other higher order processing as a result of reducing the total cognitive ability. However, our findings demonstrate that even modest visual degradation impacted on cognitive test performance in younger subjects, slowing down test performance rather than increasing the number of errors made.

In summary, these results demonstrate that performance on some cognitive tests may be impaired in the presence of filters which simulate the effects of mild to moderate cataracts and have potential implications for cognitive testing. The results suggest that for cognitive tests, similar to those included in this study, it is critical to ensure that the contrast of testing materials is as high as possible and to identify whether patients have any ocular diseases that might impair contrast sensitivity, such as cataracts and glaucoma, and to interpret cognitive test performance in the light of these deficits. The results also provide the basis for further studies which determine the critical level of contrast sensitivity below which there is a decrease in performance on these specific cognitive tests and to identify the scope of cognitive tests for which these effects are relevant. The findings also have potential implications for the design of stimulus displays and panels, including those used in vehicle dashboards and in-vehicle displays.

These results suggest that, even for younger drivers, these displays should be of the highest contrast possible in order to minimise the time required to extract relevant information and therefore the time that a driver needs to take their eyes off the road.

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Table 1: Group mean visual and cognitive performance as a function of visual impairment condition

	Mean Performance (SE)			ANOVA	p value
	0 Filter	1 Filter	2 Filters	(df 2,58)	
Visual acuity	-0.09 (0.01)	-0.00 (0.01)	0.15 (0.01)	267.4	<0.001
Pelli-Robson	1.98 (0.02)	1.57 (0.02)	1.12 (0.02)	593.9	<0.001
Digit Symbol Substitution Test (correct in 90s)	73.23 (2.31)	70.73 (2.45)	62.87 (2.08)	52.36	<0.001
Digit Symbol Substitution Test (errors)	0.17 (0.08)	0.10 (0.06)	0.30 (0.09)	1.79	0.175
Trail Making Test A (s)	20.68 (0.91)	20.94 (0.97)	28.62 (1.44)	23.61	<0.001
Trail Making Test A (errors)	0.10 (0.07)	0.13 (0.06)	0.03 (0.03)	0.69	0.504
Trail Making Test B (s)	45.02 (1.73)	46.29 (1.91)	63.48 (3.07)	32.79	<0.001
Trail Making Test B (errors)	0.23 (0.09)	0.20 (0.07)	0.13 (0.06)	0.43	0.653
Stroop D (s)	10.54 (0.42)	10.71 (0.39)	12.06 (0.45)	14.15	<0.001
Stroop D errors	0.00 (0.00)	0.034 (0.034)	0.069 (0.048)	1.00	0.374
Stroop W (s)	11.76 (0.37)	12.30 (0.42)	13.24 (0.58)	6.33	0.003
Stroop W errors	0.00 (0.00)	0.034 (0.034)	0.034 (0.034)	0.491	0.614
Stroop C (s)	16.63 (0.66)	16.01 (0.51)	17.89 (1.00)	2.64	0.08
Stroop C errors	0.034 (0.034)	0.034 (0.034)	0.172 (0.087)	2.10	0.10
Stroop (C-W) (s)	4.87 (0.52)	3.72 (0.33)	4.65 (0.82)	1.19	0.31