Glaucoma and Computer Use: Do Contrast and Color Enhancements Improve Visual Comfort in Patients ?

Clémentine Garric, Jean-François Rouland, Quentin Lenoble

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AUTHORS

Clémentine Garric [1,2], Jean-François Rouland [1,2,3] & Quentin Lenoble [1,2]

[1] Univ. Lille, Inserm, CHU Lille, U1172 - LilNCog (JPARC) - Lille Neurosciences & Cognition, F-59000 Lille, France
[2] Univ. Lille, CNRS, CHU Lille, UMR 9193, SCALab, Sciences Cognitives et, Sciences Affectives, F-59000 Lille, France.
[3] Ophthalmology Department, Claude Huriez Hospital, University of Lille, Lille, France

CORRESPONDING AUTHOR

Quentin Lenoble, Faculté de Médecine de Lille,
Pôle Recherche, 5iem et. Ouest, 1 Place de Verdun, Lille 59000, France
(email: quentin.lenoble@univ-lille.fr)

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Low vision, glaucoma, computer use, quality of life, eye-tracking, image enhancement

ABBREVIATIONS

CGI: Computer Graphical Interface
CLV: Central Loss of Vision
CS: Contrast Sensitivity
HFA: Humphrey Field Analyzer
I.T.: Information Technology
NEI VFQ-25: National Eye Institute Visual Functioning Questionnaire
PCA: Principal Component Analysis
PLV: Peripheral Loss of Vision
POAG: Primary Open-Angle Glaucoma

Abstract

Purpose: To estimate the impact of glaucoma on computer use and assess specific adaptations of the graphical interface to this form of visual impairment.

Design: Prospective experimental cohort study.

Participants: Forty-nine participants were recruited: 16 patients with primary open-angle glaucoma (POAG, mean±SD: 62.7±5.6 years old), 17 age-matched participants (mean±SD: 59.1±8.3 years old) and 16 young controls (mean±SD: 23.3±2.1 years old).

Methods: An ophthalmologic examination prior to the study evaluated the level of visual loss (MD), visual acuity (LogMar) and contrast sensitivity (CS) of the POAG patients. Each participant underwent the following measurements: an Information Technology (I.T.) experience questionnaire, a preference task monitored by eye-tracking, and a feed-back session. The experimental task was based on ecological computer scenes following three enhancement levels (low, medium and high), determined by gradual modulation of contrast, luminance and color. Participants were asked to select the most readable and comfortable stimulus between four images displayed on the screen: the original computer scene and three enhanced versions.

Main outcome measures: Clinical, oculomotor and subjective data were computed together in a multivariate model by using a principal component analysis (PCA).

Results: The PCA revealed three principal components accounting for 72% of the total variance of the data and showed a greater need for enhanced computer scenes in glaucoma patients, an equal preference for low and medium enhancement within the three groups, and significantly longer oculomotor behavior in the patients group. Subjective reports of difficulty to use I.T. due to vision were correlated with visual impairment and high enhancement preference. Contrast sensitivity (CS) was critical to explain the main variations of the data. A reduced CS had a significant effect on the preference for enhanced computer scenes ($r = -0.431$; $p < 0.002$) and a less effective exploration velocity ($r = 0.428$; $p < 0.002$).

Conclusions: Glaucoma alters the global exploration of computer scenes. High enhancement of the graphical interface could improve visual comfort during computer use. Subjective patients' reports underline the importance of including I.T. questions in visual-related quality-of-life questionnaires.

Introduction

Glaucoma is the progressive degeneration of the optic nerve fiber, resulting in loss from peripheral to central vision that can critically lead to blindness. The pathology usually affects adults over 40 years old, and its prevalence is increasing considerably with the aging of the world population.[1] Appropriate treatments tend to limit the progression in visual field loss but damage is irreversible and affects everyday life functioning.[2,3] Previous studies have shown that the supposedly spared central vision in glaucoma presents certain impairments, such as a decrease in contrast sensitivity[4–6] and alteration of luminance adaptation.[7] Furthermore, in tasks involving higher levels of visual cognition capacities, some authors have demonstrated that glaucoma affects complex visual processing, such as object categorization or face recognition in ways that are not predictable by their extent of visual field loss.[8–10] Ganglion cell damage in glaucoma may also affect oculomotor behavior. For instance, by measuring eye movements towards static and moving targets in central vision, Lamirel et al. (2014) demonstrated that, compared to age-matched controls, saccades in patients presented delayed latency and decreased precision.[11] Altogether, these studies bring new understanding of the disease by testing the limits of patients' visual capacities at threshold stimuli on a computer screen (low contrast, decreasing size, filtered spatial frequency, repetitive target movements, …). However, while most of the experimental paradigms are computer-dependent, few investigations have focused on the impact of glaucoma on Information Technology (I.T.) use with ecological measures. Recently, Asfaw et al. assessed eye movements during free exploration of natural scenes on computer [12] and found altered saccadic movements and oculomotor compensation strategies in patients with glaucoma. However, participants were tested monocularly and these results were found by comparing worse and better eye recordings. To our knowledge, no study has yet investigated the binocular visual performance of patients with glaucoma on ecological computer tasks compared to normal aging subjects. We hypothesized that impairment due to glaucoma, previously measured at threshold on experimental paradigms, could have an impact on common

computer use. The specific knowledge of the limits of visual functions could lead to new tools to enhance the I.T. experience of patients.

A translational area of research between vision science, ophthalmology and technology aims at developing high-tech aids for the rehabilitation of the visually impaired. Moshtael et al. (2015) reviewed the digital image processes used to maximize the residual vision in low-vision patients.[13] To name a few, contrast, contour enhancement and edge detection techniques were used on images or videos to create high-tech aids and assess visual performance improvement in low-vision patients (i.e. object recognition, reading). In this review, only one study among the twelve selected considered peripheral loss of vision (PLV) and the peripheral deficit condition was an artificially simulated tunnel vision.[14] The main clinical target for these aids remains patients with central vision loss, i.e. age-related macular degeneration. Considering the previously mentioned central vision impairment of patients with glaucoma, such technological rehabilitation could benefit PLV patients. One may hypothesize that modulating specific parameters of the computer graphical interface (CGI), such as increasing contrast along with adjusting luminance intensity, could create a more suitable digital environment for glaucomatous patients. Furthermore, results from the central loss of vision (CLV) aid literature could also provide relevant tracks to follow. Watson et al. (2012) hypothesized that by developing stimuli enhanced according to the visual properties of the residual peripheral vision in patients with CLV, they could improve their capacity to read or recognize facial expressions.[15] Jittered stimuli (with low contrast and low spatial frequency) improved the visual abilities of CLV patients with advanced symptoms, but not in the group with moderate vision loss. In line with these findings, we postulated that progressive enhancement of stimuli according to the visual properties of central vision (i.e. a progressive contrast and color heightening in computer scenes) could be adapted for various glaucoma stages and could optimize the readability of computer scenes for PLV patients.

Further evidence of the lack of information on the I.T. experience of glaucomatous patients, or low-vision patients in general, can be found in visually related quality of life (QoL) questionnaires such as the 25-item *National Eye Institute Visual Functioning Questionnaire* (NEIVFQ-25[16]). While these questionnaires are commonly used to measure everyday life difficulties of low-vision patients,[17,18] patient-reported I.T. experience is still not included.

In this context, the aim of the present study was to fill the gap between the lack of information concerning the possible impact of glaucoma on I.T. use (subjective experience and oculomotor behavior) and graphical interface adaptation on computer screens for PLV patients. To do so, we built gradual enhanced versions of ecological computer scenes and tested three groups of participants (young controls, age-matched controls and glaucoma patients) on a preference task, monitored by an eye-tracker. We aimed at exploring the I.T. experience and its enhancement in glaucomatous and normal aging populations, considering the four critical dimensions of the study: subjective I.T. experience, visual assessment, enhancement preference measures and oculomotor behavior.

Methods

Participants

Forty-nine participants were recruited for this study: 16 patients with primary open-angle glaucoma (POAG, mean±SD: 62.7±5.6 years old), 17 age-matched participants (mean±SD: 59.1±8.3 years old) and 16 young controls (mean±SD: 23.3±2.1 years old). All participants provided written informed consent before the experiment. They were required to have a corrected binocular visual acuity of at least 0.2 logarithm of the minimum angle of resolutions units (log MAR), no neurological history and no ophthalmological condition other than glaucoma, except for uncomplicated cataract surgery. According to the results on the Humphrey Field Analyzer (HFA; Carl Zeiss Meditec, Dublin, CA), three possible stages of the pathology were defined on the basis of the worst eye Mean Deviation (MD) score as: early (from 0.00 to -6.00 dB), moderate (going from -6.01 to -12.00 dB) and severe

glaucoma (lower than -12.00 dB). Clinical data is detailed in **Table 1**. Each participant over 60 years old (controls and glaucoma patients) was cognitively assessed with the Mini Mental State Examination (MMSE[19]) and had to reach a score above 26/30 to be included. Binocular contrast sensitivity was assessed with a Pelli-Robson chart and scored in log CS. These clinical evaluations were followed by the experimental procedure: an I.T. experience questionnaire, a forced-choice experiment (the preference task) monitored by eye-tracking, and a feedback session. This protocol was approved by our institutional ethics committee (VAO 2019-346-S71) and adhered to the Declaration of Helsinki.

*[Insert **Table 1 - Demographic and clinical data of participants with POAG]***

I.T experience questionnaire

The I.T. experience questionnaire was created for this study to measure the global experience of the participants towards information technologies (original French version available in **Supplemental Material**). The aim was to collect information efficiently about the type of device used, the frequency of use and the estimated user level (five items), as well as an estimation of potential difficulties encountered due to vision (four items). Based on the NEIVFQ-25 format, which is widely used to quantify quality of life in low-vision patients, the last four items were focused on everyday life I.T. common tasks (i.e. reading, searching for icons on a computer screen, reaching a target with a mouse) and the answers were given on a scale from (1) “No difficulty at all” to (5) “Use stopped because of visual difficulties”. An average difficulty score was computed from these four items.

Demographic details by groups are shown in **Table 2**.

*[Insert **Table 2**- Contrast sensitivity and I.T. experience demographic data]*

Apparatus

Participants were seated in a dimly lit room with controlled artificial lighting. The distance from the screen (15.6-inch screen; resolution 1920x1080 pixels) was set at 57 cm with a chin rest. The computer was a Dell Precision M4800 equipped with an Intel Core I7 processor and 16 GB RAM. The stimuli were displayed synchronously with eye-tracking recording thanks to the *Experiment Center* software and a RED-m eye-tracker model (250 Hz) by *SensoMotoric Instruments* (*SMI)*. Participants were tested binocularly, wearing their usual correction.

Stimuli

To create ecological computer scenes as stimuli, we gathered 30 screenshots of web pages of everyday life use of the internet (weather website, recipes, maps, …). According to the intensity of contrast, color and luminance from original computer scenes, three experimental levels of image enhancement were created using the *Gnu Image Manipulation Program* (GIMP, 2.10.18) free and open source. Pictures were handled in RGB mode (Red-Green-Blue) by the program. Pixel properties on RGB values were converted by different levels of percentage on contrast, balanced luminance, and color saturation for each picture. The three levels of image enhancement were defined as follows: (1) *Low enhancement* was processed by increasing contrast (mean±SD: 58% ± 25) and balancing luminance (mean±SD: -33% ± 28). Visually, *low enhancement* pictures depict a slight increase in contrast. (2) *Medium enhancement* corresponded to a *low enhancement* processing merged with color increment (mean±SD: 96% ± 26). Pictures with *medium enhancement* appeared to the participants as more contrasted and more colored than the original picture. (3) *High enhancement* processing applied high saturation of the original version without counterbalancing luminance. Descriptively, the high enhancement was is radically different from the original and accentuated contrast, luminance, and color perceptions in a way that contours and lines were more detectable. In the end, the image database included 120 stimuli (922 × 518 pixels), namely four versions of each of the 30 screenshots (**Fig. 1**): *original* (i.e. unenhanced), *low*, *medium* and *high*

version. To rigorously validate the stimuli set, the physical properties of the 120 stimuli were analyzed, compared among the three enhancement levels, and adjusted using GIMP.

[Insert Figure 1: Experimental design of one trial of the preference task]

Procedure

The preference task was used to measure the most readable and comfortable image enhancement of ecological computer scenes. Participants were tested in two blocks of 30 trials, after calibration of the eye tracker and two training trials. The trial structure began with a fixation phase ranging from 400 ms to 600 ms, with a red fixation cross at the center of the screen. The fixation phase was followed by the simultaneous display of four versions of one computer scene (**Fig. 1**) and a cursor at the center (on the red fixation cross). Participants were instructed to carefully observe the four stimuli and to manually select the most readable and comfortable display, thanks to the cursor on the screen. There was no time restriction and the next trial started after the selection. The 30 trials of each block corresponded to the 30 randomly ordered screenshots. After the end of the first block and a short break (duration decided by the participant), the same stimuli were shown in a different randomized order during the second block. Each version (*original, low, medium* and *high enhancement*) was equally represented over the 60 trials on the four portions of the screen (i.e. upper left, upper right, lower left, lower right) and not displayed in the same position between the first and the second block. At the end of the two blocks, open-ended feedback questions were answered. The answers were recorded to let the participants describe their preference and their choices during the experiment. Critical key words and preference types were analyzed for each of the 49 participants, then gathered into different categories to classify their answers on a Subjective Enhancement Preference Scale, ranging from *(1) None* to *(5) Highly augmented pictures*.

Data Analysis

The data was analyzed in two ways. First, single variable analyses were designed to assess how the main variables of the experimental task were related to vision loss (comparison between healthy participants and patients, along with correlation between clinical measures and performances). Secondly, the Principal Component Analysis revealed correlations between objective (clinical data, oculomotor data) and subjective (preference task, I.T. questionnaire) records. The analyses were conducted with Statistical Package for the Social Sciences (SPSS, version 25).

Single variable analyses

Non-parametric tests (Kruskal-Wallis) were used to assess differences between groups for demographical data (**Table 2**) and individual variables. A Bonferroni correction was conducted to test groups pairwise. When variables showed a normal distribution but heterogenous population variances, a pairwise comparison was performed with the Welch t-test. Correlations between clinical data and behavioral data were assessed by Spearman's rank correlations. Statistical significance of the correlation coefficient (r) was set at $P < 0.05$.

Principal Component Analysis

Principal component analysis (PCA) is a multivariate statistical method generally applied to reduce high-dimensional data sets into groups of interrelated variables called principal components (PC). PCA starts with a covariance matrix computation between every variable. Based on this matrix, the calculation of eigenvalues and eigenvectors helps sort principal components by relevance: the first principal components have the highest eigenvalue, meaning that they retain the optimized rate of variation present in all original variables and eliminate redundant information. Each PC with an eigenvalue below 1 provides less information than an individual variable variation (Kaiser criterion). The number of PC retained usually accounts for at least 50% of the total variance of the original data set. Eigenvectors are converted to factor loadings that characterize the weight and nature of the correlation of an individual variable within a PC.

We performed a PCA on our data set to statistically identify the link between *visual assessment, I.T. experience, preference measures* and *oculomotor behaviors* defined below. Two variables were included in the visual assessment: *contrast sensitivity* (log CS) and the *clinical visual deficit* on a 4-level scale: 1-None, 2-Corrected vision, 3-Monocular Glaucoma, 4-Binocular Glaucoma. The I.T. experience was represented by the *I.T. difficulty score due to vision* (**Table 2**).

We evaluated four preference measures:

- *Behavioral preference* as the percentage of original, low, medium and high enhancement manually answered on 60 trials ($P_{original}$, P_{low} , P_{medium} , P_{high});
- *Visual-oriented preference* as the mean dwell time per enhancement version (sum of fixation durations and saccades inside an Area Of Interest (AOI)) standardized by the total mean dwell time per AOI of a participant;
- *Global enhancement preference* as the odds of selecting an enhanced version over the original[20]: $\frac{P_{enhanced}}{(1-P_{enhanced})} = \frac{(P_{low}+P_{medium}+P_{high})}{P_{original}}$, greater than 1 when enhanced versions were preferred over the original, equal to 1 when there was no preference and lower than 1 when the original version was mainly chosen;
- *Subjective enhancement preference* as the rank on the subjective enhancement preference scale calculated from the feedback analysis.

Oculomotor behaviors were declined in four variables:

- *Visual attention delay* as the global mean dwell time per AOI;
- *Exploration time* as the global mean delay between stimuli display and preference decision;
- *Exploration velocity* as the global mean scanpath efficiency in pixels per second;
- *Total revisits* as the sum of fixations towards an AOI already targeted during a trial.

Altogether, 17 variables were submitted to PCA using SPSS. Principal components were retained only when the eigenvalue was greater than 1. Independent variables were considered as relevant if the absolute value of factor loading exceeded 0.5. The factor loading indicates whether the variable within the PC is correlated positively or negatively. Each PC was identified and labeled through an overview of the various classifications of variables (*visual assessment, I.T. experience, oculomotor behavior* and *preference measures*) and the nature of their interactions. Individual factor scores from each PC were extracted for each participant and used as behavioral covariates in the group comparison analysis. For each PC, a one-way analysis of variance (ANOVA) was applied to calculate differences in factor scores across the three groups. The Bonferroni adjustment for type 1 errors was used for post-hoc multiple comparisons.

Results

This study included 49 participants (n=16 young controls, n=17 age-matched controls and n=16 glaucoma patients). The global demographic characteristics and I.T. use measures are displayed in **Table 2**. Age difference was statistically validated. Contrast sensitivity in glaucoma patients was significantly lower than in the two control groups ($P < 0.001$ Kruskal-Wallis test and $P < 0.001$ Bonferroni pairwise comparison). Among the participants, no significant difference was found between the three groups regarding the frequency of computer use. Main group effects explained by significant differences between young controls and glaucoma patients were found in the percentage of tablet users and I.T. difficulty score due to vision ($P < 0.05$ Kruskal-Wallis test and $P < 0.05$ Bonferroni pairwise comparison).

Single variable analyses

Did the different groups have specific enhancement preferences?

The behavioral preferences ($P_{original}$, P_{low} , P_{medium} , P_{high} manually selected) were averaged by group (**Figure 2A**): a main group effect was found for $P_{original}$ and P_{high} (respectively Kruskal-Wallis; $P = 0.008$ and $P = 0.001$). On average, young controls selected more original and fewer high-

enhancement versions than age-matched controls (Welch t-test; *P*-values < 0.05) and glaucoma patients (respectively, Welch t-test *P*-value = .002 and .001). No behavioral preference differences were found for low- and medium-enhancement versions (*P* > 0.05; Kruskal-Wallis). No significant differences were found for enhancement preference between the various glaucoma stages (**Figure 2B**, *P* > 0.05; Kruskal-Wallis).

[Insert Figure 2: Group comparison of enhancement preference]

Determining the effect of visual impairments on enhancement preference and oculomotor behavior

Significant correlations were found across all participants between contrast sensitivity and global enhancement preference (**Figure 3A**, Spearman's rho = - 0.43; *P* = .002), as well as between contrast sensitivity and exploration velocity (**Figure 3B**, Spearman's rho = 0.43; *P* = .002). However, no significant correlations were found within the patient group between Mean Deviation (MD) and the main variables, global enhancement (**Figure 3C,** Spearman's rho = -.32; *P* = .12) and exploration velocity (**Figure 3D,** Spearman's rho = 0.05; *P* = .42).

[Insert Figure 3: Behavioral and oculomotor data correlated to visual impairment]

Principal Component Analysis

Is there a link between the overall experimental data (objective/subjective) and clinical measures?

The PCA revealed three principal components accounting for 72% of the total variance of the data. PC1 involved nine variables and accounted for 31% of the total variance, PC2 involved four variables and accounted for 22.7% of the total variance and PC3 involved four variables and accounted for 18.3% of the total variance. Principal components are detailed in **Fig. 4A** and compared by group in **Fig.4B**.

[Insert Figure 4: Principal Component Analysis]

The first principal component (PC1) contained six preference measures in favor of enhancement preference: positive factor loading for global and subjective enhancement preference, percentage chosen and visual-oriented preference of high enhancement version, correlated with negative factor loading of percentage chosen and visual-oriented preference of original versions. PC1 also represented visual impairment with a negative factor loading of contrast sensitivity and exploration velocity, and a positive factor loading on the I.T. difficulty due to vision score. PC1 was labeled "*Graphical Interface Enhancement Needed*" and showed a main group effect (F= 12.16, $P < 0.001$). As shown in **Fig. 4B**, this component was significantly lower in the young control group compared to the age-matched group ($P = 0.02$) and the glaucoma patients ($P < 0.001$). Glaucoma patients presented a higher mean factor score than age-matched controls (statistical tendency; $P = 0.11$ Bonferroni post-hoc correction, $P = 0.06$ on a t-test comparison). The second principal component (PC2) only contained preference measures with positive correlations between the percentages of *low* and *medium enhancement* versions and the visual-oriented attention towards them. PC2 was labeled "*Average Stimuli Preference"* and no main group effect was found (F = 1.14, $P = 0.34$). Results are illustrated in **Fig. 4B**. The third principal component (PC3) included four visual measures: *clinical visual deficit* score, *total* number of *revisits* on a computer screen version, *visual attention delay* and *exploration time,* which were positively correlated. PC3 was labeled "*Longer oculomotor behavior"* and demonstrated a main group effect (F= 13.40, $P < 0.001$). As illustrated in **Fig. 4B**, the mean factor score of this component was significantly higher in glaucoma patients than in aged-matched controls ($P = 0.002$) and young controls ($P < 0.001$).

Discussion

Information Technology is increasingly present in everyday life activities and requires both low-level and high-level visual functions. Gathering clinical, behavioral, oculomotor and subjective data, this exploratory study was designed to provide an overall view of the impact of glaucoma on I.T. experience and the possible enhancement of visual comfort during computer use. This multifactorial

experiment evaluated the computer graphical interface enhancement preferences of patients with glaucoma, age-matched controls and young controls, along with oculomotor behavior monitored by eye-tracking. Using a principal component analysis, our statistical approach was innovative and demonstrated correlations between subjective and objective enhancement preferences and specific visual impairment.

I.T. experience

In this study, the socio-demographical data collected during the I.T. experience questionnaire demonstrated that glaucoma patients, age-matched controls and young controls presented the same rate of computer and smartphone use, despite the generation gap. Interestingly, the main difference between the devices appeared to be the use of tablets, with a higher percentage of users within the glaucoma group (62% of tablet users reported, compared to 29% among age-matched controls and 13% among young controls, **Table 2**). This suggests that while computers and smartphones could be sufficient for controls, an in-between device with a larger screen could be more suitable for low-vision patients. Moreover, the difficulty score, computed from five items based on NEIVFQ and adapted to our I.T. experience questionnaire, was significantly different between the groups, and glaucoma patients presented the highest mean score. In a highly digitized society, these results emphasize the importance of including I.T.-related questions when assessing the quality of life of glaucoma patients, even in the elderly.

Enhancement Preference

Individual variable analysis highlighted that while young controls mostly selected original computer scenes, age-matched controls and glaucoma patients preferred enhanced stimuli. High enhancement versions were mostly avoided by young controls and preferred by older participants. The absence of significant difference between glaucoma patients and age-matched patients revealed that CGI enhancement could generally benefit elderly people, with or without visual impairment. This is in line with previous work demonstrating that normal aging involves a natural decline in visual functions[21]

and more specifically in low-level vision.[22,23] Therefore, boosting physical parameters of computer scenes, such as contrast and color, could also create a more suitable digital environment for elderly people. Regarding the exploration of the impact of glaucoma stages, no differences in enhancement preferences were found between early, moderate and severe glaucoma. However, in severe glaucoma, the tendency to prefer gradually higher enhancement underlines a possible link between the degree of vision loss and the necessity for increased CGIs. In line with this hypothesis, our data demonstrate that reduced contrast sensitivity is correlated with a stronger preference for enhanced computer scenes. Further investigations with larger cohorts of various glaucoma stages could statistically validate the correlation between the degree of enhancement needed and the severity of visual impairment.

Principal component analysis and oculomotor behavior

In the present study, PCA was a robust tool to establish the global links between objective, subjective, experimental and clinical data. The first principal component revealed a strong correlation between visual impairment and enhancement preference (objective and subjective), in favor of high enhancement. A group comparison highlighted this for the "*Graphical Interface Enhancement Needed"* component*:* young controls were not concerned, age-matched controls were neutral and glaucoma patients largely fulfilled this profile. This result shows that on the basis of everyday life reports, subjective feedback and experimental measures, glaucoma patients presented a greater need for CGI enhancement than the visually healthy groups. PC2, labeled "*Average Stimuli Preference"* demonstrated that low and medium enhancement preference was equally shared between the groups. Targeting a central vision-biased enhancement in the construction of stimuli, the results of PC1 and PC2 indicate that low and medium enhancement could suit all kinds of populations, whereas high enhancement seems to be better suited to low-vision patients.

The third principal component demonstrated that glaucoma patients presented significantly longer oculomotor behavior to explore ecological computer scenes. PC3, labeled *"Longer oculomotor*

375 *behavior",* gathered a longer exploration time and visual attention delay by stimuli, as well as a
376 higher number of revisits: stimuli that had already been scanned needed to be explored again. Our
377 results suggest that these compensated oculomotor behaviors are more frequent in glaucoma
378 patients than in visually healthy groups, and that they are correlated with higher clinical visual deficit.
379 To assess whether the longer performances could be linked to a specific deficit, we computed the
380 correlation between participants' exploration velocity and contrast sensitivity, and found that
381 reduced contrast sensitivity was associated with a decreasing exploration velocity. Previous studies
382 have shown that glaucoma patients compensate their peripheral visual field loss with various eye-
383 movement strategies, which have been measured during the exploration of a traffic scene,[24] natural
384 TV watching[25] or monocularly during natural scene exploration within central vision on a computer
385 screen.[12] Various types of compensation have already been identified: physical change in eye
386 movement (i.e. angular difference between two saccades), higher rate of oculomotor behavior
387 compared to controls or longer delays of exploration to perform a task.[26] Our findings indicate that
388 glaucoma patients may use these oculomotor strategies binocularly when viewing ecological
389 computer scenes.

390 This study provides new understanding regarding the I.T. experience of patients with glaucoma and
391 that of the normal-aging population. However, some limitations must be acknowledged. First, we
392 measured computer experience on a 15.6-inch laptop, which could be small for participants who are
393 used to a desktop computer. Indeed, since patients seemed to prefer tablets to a smartphone, we
394 assume that a bigger screen and high resolution are important to improve their experience.
395 Nowadays, high quality monitors are more common, quite affordable and could already constitute an
396 option to enhance residual vision in glaucomatous users. Second, by measuring oculomotor behavior
397 on a preference task, the various time-dependent data observed could be confounded between
398 visual performance and time related to decision-making. Therefore, we explored multiple reliable
399 assessments by adding oculomotor measures standardized by the distance scanned on the screen
400 (i.e. exploration velocity [px/s]) or by considering variables without a time dimension (i.e. total

amount of revisits on a stimulus). Third, while the comparison between the different glaucoma stages is an important focus to better understand the development of specific visual enhancement (adapted to the degree of vision loss), the present data set was limited by the sample size of the subgroup (early, moderate, severe) of glaucomatous patients. Finally, enhancement preference may be quite different from the effective enhancement of CGI adapted to patients with glaucoma. Further investigations are needed to establish an objective link between enhancement and the possible improvement of patients on specific computer tasks involving their visuo-spatial capacities.

Overall, we conclude from the subjective reports of glaucomatous patients that I.T. experience and the difficulty to use digital devices due to vision issues are significant measures to consider in visual-related quality of life questionnaires. Graphical enhancement generally made ecological computer scenes more suitable for glaucoma patients and age-matched controls, while young controls showed a distinct preference for the original versions. However, by using principal component analysis to evaluate everyday life reports, subjective feedback and experimental data together, patients with glaucoma demonstrated a greater need for computer graphical interface enhancement than the visually healthy groups. Moreover, contrast sensitivity, which was significantly reduced in glaucoma patients, was a central measure to understand enhancement preference variations and differences in oculomotor behavior. Glaucoma seems to affect the global exploration of a computer screen and involves a strategic change in eye movements with longer oculomotor behavior. Finally, our findings provide better understanding of the impact of glaucomatous visual loss on everyday activities, such as computer tasks, and give important cues for developing adapted computer graphical interfaces for such visual impairment.

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Figure Legends

Figure 1: ***Experimental design of one trial of the preference task***

[upper left] – original computer scene, [upper right] – high enhancement, [lower right] – low enhancement and [lower left] – medium enhancement.

Figure 2: ***Group comparison of enhancement preference***

*[**A**] for young controls (blue), age-matched controls (orange) and glaucoma patients (gray); [**B**] for dissociated glaucoma stage: early (light grey), moderate (dark grey) and severe (black dotted line). ** P-value < 0.01, * P < 0.05*

Figure 3: ***Behavioral and oculomotor data correlated to visual impairment***

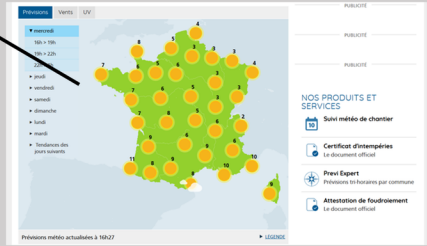
Scatterplots with fitted regression lines illustrating the relationship between: ***[A] contrast sensitivity and the global enhancement preference*** *(1: no preference, 1 < original version preference, > 1: enhanced version preference, > 10: only few original versions selected);* ***[B] contrast sensitivity and exploration velocity*** *(scanpath in pixels per sec);* ***[C] MD and Global enhancement preference****;* ***[D] MD and Exploration velocity.***

*The Spearman correlation coefficient (r) is plotted on the two graphs (top-left): ** P-value < 0.01*

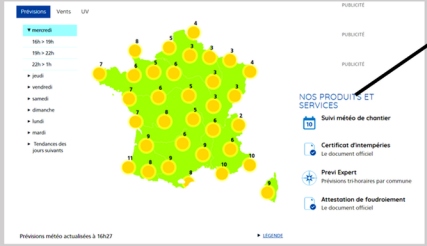
Figure 4: ***Principal Components Analysis***

[A] Principal components compositions resulting from PCA. *Variables gathered within a principal component retain the optimized rate of variation present in the overall data set. One column represents one principal component. Factor loading scores illustrate the nature of the relation between the variables within a principal component: either negative (factor loading < - 0.5; from light to dark blue) or positive (factor loading > 0.5; from light to dark red) correlations.* ***[B] Group comparison of principal component mean factor score****: mean comparison of PC1, PC2 and PC3 factor scores. Positive or negative factor scores mean that a group is respectively congruent or incongruent with the principal component. The three groups are represented from left to right in each component: young controls (blue), age-matched controls (orange) and glaucoma patients (grey). * P-value < 0.05 ** P < 0.01 *** P < 0.001*

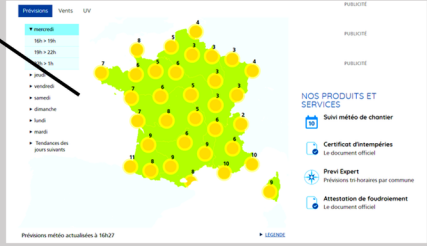
Original



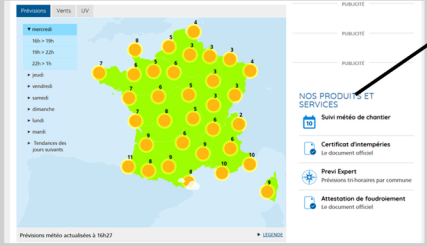
High

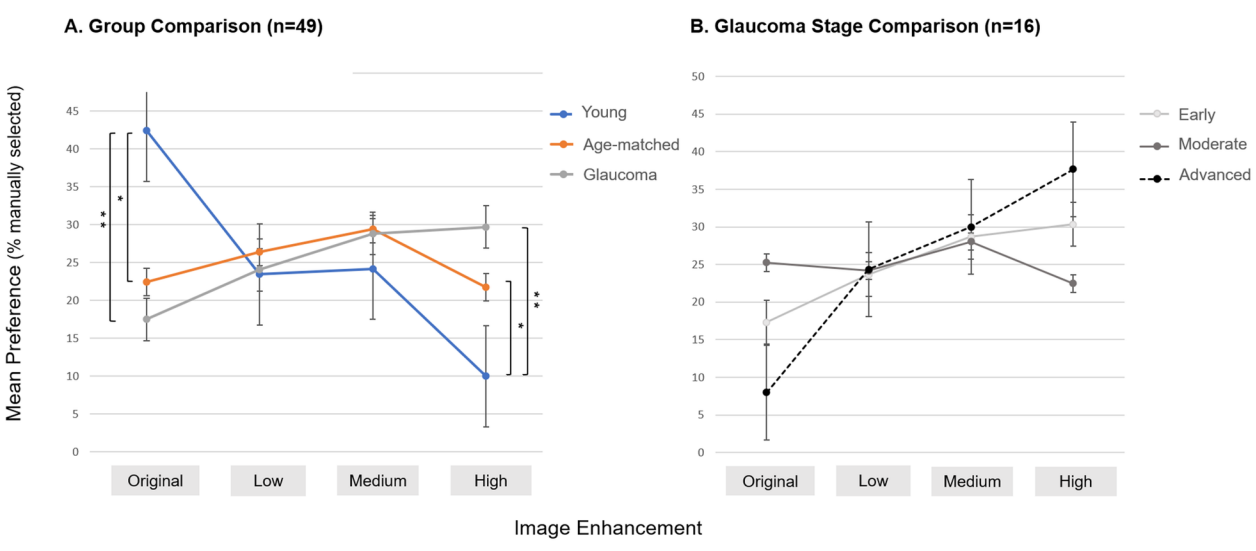


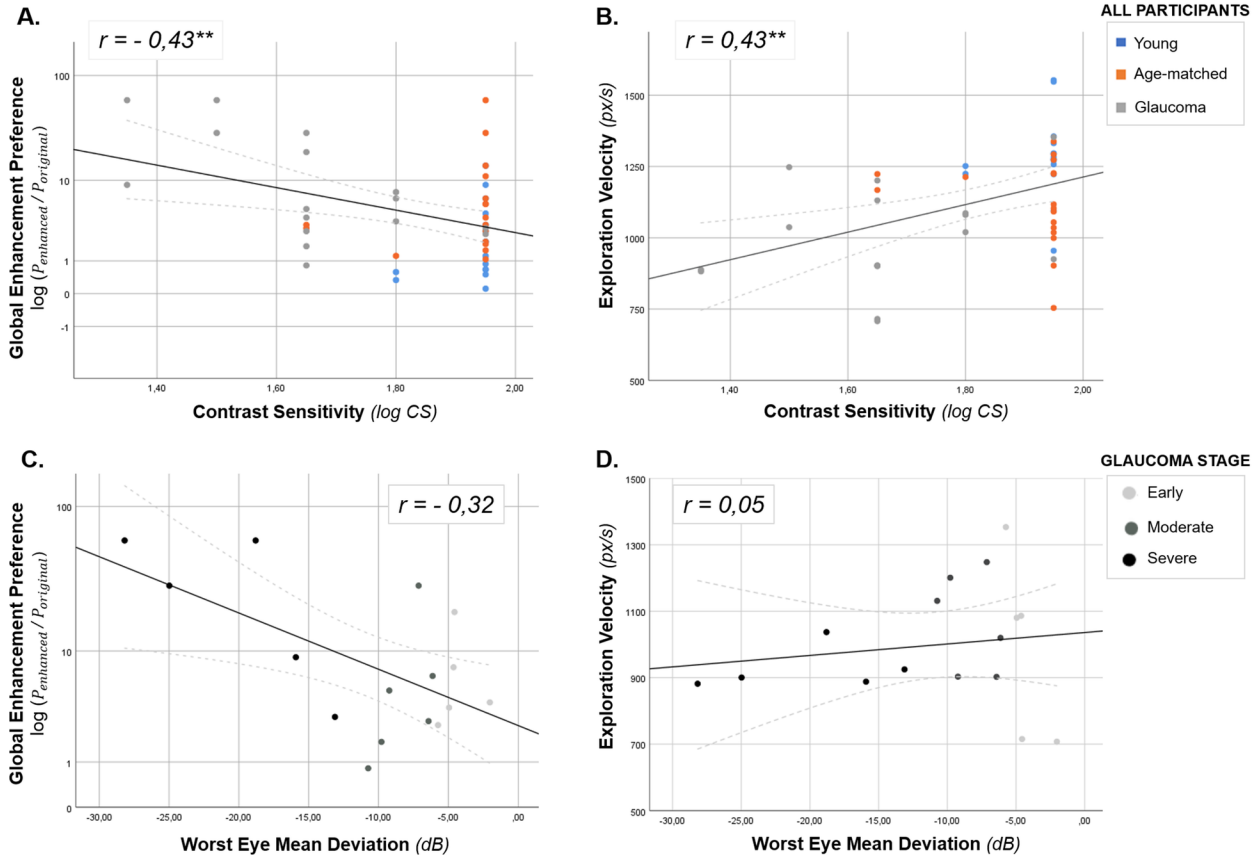
Medium



Low




A. Group Comparison (n=49)
B. Glaucoma Stage Comparison (n=16)
Mean Preference (% manually selected)
Young
Age-matched
Glaucoma
Early
Moderate
Advanced
Original
Low
Medium
High
Image Enhancement


A.
r = - 0,43**
Global Enhancement Preference
log (P_enhanced / P_original)
Contrast Sensitivity (log CS)
B.
r = 0,43**
Exploration Velocity (px/s)
Contrast Sensitivity (log CS)
ALL PARTICIPANTS
Young
Age-matched
Glaucoma
C.
r = - 0,32
Global Enhancement Preference
log (P_enhanced / P_original)
Worst Eye Mean Deviation (dB)
D.
r = 0,05
Exploration Velocity (px/s)
Worst Eye Mean Deviation (dB)
GLAUCOMA STAGE
Early
Moderate
Severe

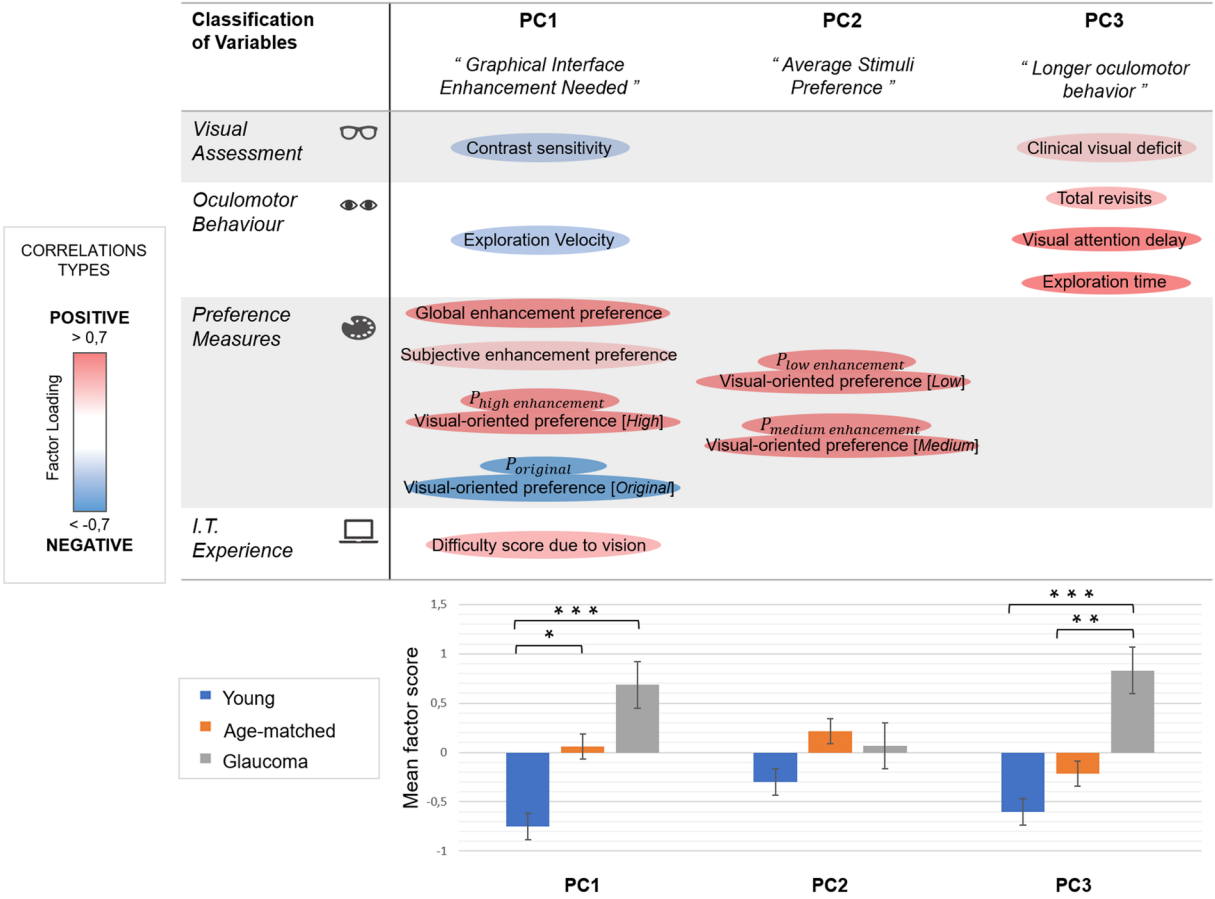

Classification of Variables
PC1
" Graphical Interface Enhancement Needed "
PC2
" Average Stimuli Preference "
PC3
" Longer oculomotor behavior "
Visual Assessment
Contrast sensitivity
Clinical visual deficit
Oculomotor Behaviour
Exploration Velocity
Total revisits
Visual attention delay
Exploration time
Preference Measures
Global enhancement preference
Subjective enhancement preference
$P_{high\ enhancement}$ Visual-oriented preference [High]
$P_{original}$ Visual-oriented preference [Original]
$P_{low\ enhancement}$ Visual-oriented preference [Low]
$P_{medium\ enhancement}$ Visual-oriented preference [Medium]
I.T. Experience
Difficulty score due to vision
CORRELATIONS TYPES
POSITIVE
> 0,7
Factor Loading
< -0,7
NEGATIVE
Young
Age-matched
Glaucoma
Mean factor score
1,5
1
0,5
0
-0,5
-1
* * *
*
* * *
* *
PC1
PC2
PC3

Table 1 - Demographic and clinical data of participants with POAG

Participants with POAG	*Gender*	*Age (years)*	*Binocular Visual Acuity (log MAR)*	*Worst Eye HFA [30 -2] MD (dB)*	*Extent [MO: Monocular BO: Binocular]*	*Glaucoma stage*	*Contrast sensitivity (log CS)*
G1	M	64	≤ 0.2	-9.79	MO	Moderate	1.65
G2	F	67	≤ 0.2	-10.74	BO	Moderate	1.65
G3	F	57	0	-5.74	BO	Early	1.95
G4	F	68	- 0.1	-24.98	MO	Severe	1.65
G5	M	58	≤ 0.2	-28.18	MO	Severe	1.35
G6	M	59	0	-6.13	MO	Moderate	1.80
G7	F	63	0	-2.03	BO	Early	1.65
G8	F	63	0.1	-9.23	MO	Moderate	1.65
G9	M	62	0.1	-6.42	MO	Moderate	1.65
G10	F	69	0.2	-7.13	BO	Moderate	1.50
G11	F	73	0.1	-4.95	BO	Early	1.80
G12	F	66	0.1	-15.92	MO	Severe	1.35
G13	M	65	≤ 0.2	-18.80	BO	Severe	1.50
G14	M	50	0.1	-4.63	MO	Early	1.80
G15	M	61	≤ 0.2	-13.12	BO	Severe	1.95
G16	F	58	0.1	-4.56	BO	Early	1.65

F, female; M, male.

Table 1- *Contrast sensitivity and I.T. experience demographic data*

CHARACTERISTICS	YOUNG (N=16)	AGE-MATCHED (N=17)	GLAUCOMA PATIENTS (N=16)
GENDER (F/M)	8/8	9/8	9/7
AGE (*) MEAN ± SD (RANGE)	23.3*** ± 2.1 (20 – 28)	59.1 ± 8.3 (46 – 73)	62.7 ± 5.6 (50 – 73)
CONTRAST SENSITIVITY (*) MEAN ± SD	1.93 ± 0.05	1.91 ± 0.1	1.66*** ± 0.2
% OF COMPUTER USERS **SMARTPHONE USERS** **TABLET USERS (*)**	100 % 100 % 13 %	94 % 100 % 29 %	94 % 100 % 62 %
COMPUTER USE FREQUENCY MEAN RATE ± SD *(1: ONCE A DAY. 2: ONCE A WEEK. 3: ONCE A MONTH. 4 : ALMORST NEVER. 5: USE STOPPED BECAUSE OF VISUAL DIFFICULTIES)*	1.06 ± 0.25	1.06 ± 0.25	1.33 ± 0.81
ESTIMATED USER LEVEL MEAN RATE ± SD *(1: EXPERT. 2: FAMILIAR. 3: NORMAL. 4: BEGINNER. 5: NO SKILLS)*	1.9 ± 0.44	2.25 ± 0.57	2.5 ± 0.89
I.T. DIFFICULTY SCORE DUE TO VISION (*) MEAN RATE ± SD *(1:NOT AT ALL. 2: A LITTLE. 3: MODERATELY. 4: A LOT. 5: USE STOPPED BECAUSE OF VISUAL DIFFICULTIES)*	1.05 ± 0.11	1.16 ± 0.21	1.35 ± 0.50

*(*) P-value < .05 group effect explained at least by a significant difference between young controls group and glaucoma patients; *** P < .001 differ significantly from the two other groups*