Initial Investigation of a Grating Stimulus as a Visual Endpoint for Human Centrifuge Research

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INTRODUCTION: G tolerance has been widely assessed using Peripheral Light Loss (PLL), but this approach has several limitations and may lack sensitivity. The aim of this study was to investigate the use of a foveal visual endpoint for centrifuge research (Grating Loss; GL) and assess its repeatability, reliability, and usability with PLL as a reference.

METHODS: A total of 11 subjects undertook centrifuge assessment. Gradual onset sessions (GOR; 0.1 $G \cdot s^{-1}$) measured both endpoints simultaneously and were performed twice, consisting of six determinations with anti-G suits activated (GOR-On) and six without (GOR-Off). Four determinations of each endpoint were also taken during rapid onset runs (ROR; 3 $G \cdot s^{-1}$). Usability was scored subjectively.

RESULTS: The GL endpoint was reached 0.3–0.5 G_z lower than PLL with each endpoint correlating strongly in GOR-Off (r = 0.93), GOR-On (r = 0.95), and ROR (r = 0.86). The GL had excellent test–retest repeatability (intraclass correlation coefficient: GOR-Off/On = 0.99, ROR = 0.92) and low within-subject variability. Between-subject variance equaled PLL in all conditions. Subjective usability endpoint ratings were equal for all conditions.

DISCUSSION: For the 11 individuals tested, the GL was a reliable, repeatable, and usable endpoint, with similar performance to PLL. GL may prove useful as a supplementary endpoint for human centrifuge research as a secondary data point or to reduce fatigue in repeated measurements. The foveal GL stimulus was lost before PLL, contrary to popular models of visual changes under $+G_z$.

KEYWORDS: +Gz, acceleration, long duration acceleration, G, visual endpoint, contrast sensitivity.

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Combat jet aircrew are exposed to accelerations many multiples that of Earth's gravity, predominately in the head-to-toe axis ($+G_z$). $+G_z$ acceleration results in a relative footward redistribution of blood, an increase in the head-to-heart hydrostatic gradient, and reduced head-level blood pressure. Decreased oxygenation of the retina leads to visual symptoms, classically described as a loss of peripheral vision ("greyout" or "peripheral light loss"), progressing with increased $+G_z$ to central visual loss ("blackout" or "central light loss"). Due to a positive intraocular pressure (mean 14 mmHg)[26] and the greater susceptibility of retinal perfusion than cerebral perfusion to a reduction in blood pressure, visual symptoms occur at lower G_z than G-induced loss of consciousness (G-LOC).

G tolerance is generally defined as the $+G_z$ level at which a specific experimental endpoint is reached. Endpoints must be easily identifiable, repeatable, and have low interindividual variability associated with its identification. While it has frequently been suggested that physiological measures be used as objective endpoints, identifying a single threshold that achieves these requirements has proven difficult.[12,13,25] The retinal and cerebral impacts of $+G_z$ exposure provide a variety of more consistent and usable endpoints. While subjective in nature,

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these are more directly relevant to in-flight risks. Visual methods using a horizontal "light bar" mounted at eye level with a central focal light and two or more peripheral lights are commonly employed and can provide two distinct endpoints: 1) peripheral light loss (PLL), the point at which the peripheral lights can no longer be identified; and 2) central light loss (CLL), the point at which the central focal light is not visible. The most commonly employed method is PLL due to the greater margin between PLL and G-LOC.

Despite the use of PLL for many decades, it is not without limitation. During testing of advanced anti-G suits by the UK RAF, it was the authors' experience that at high levels of +G_z acceleration, subjects reported that peripheral lights persisted despite significant central dimming, a phenomenon which has been similarly reported by other research centers.[22] This potentially renders the technique relatively insensitive at higher acceleration levels. Additionally, the PLL technique relies on the assumption of symmetrical tunnelling of vision, although initial changes have been shown to be more profound in the medial, rather than lateral, visual field of each eye.[10] Case studies of unequal visual field loss have been reported,[17,20] which may explain in part why subjects report varied visual field changes, affecting how they interpret both PLL and CLL.[4] With consistent settings, a single determination of PLL has been found to be "moderately unreliable", with 10% of the difference in G tolerance between individuals attributable to measurement error.[16] This is further affected by a lack of standardization of test parameters, with PLL measured at a wide ranges of angles, including 30°,[23] 50°,[14] and 60°.[19,25] Other factors such as size, color, brightness and uniformity of the lights,[9] and ambient lighting conditions[2] will also affect G tolerance measured in this manner.

By exploiting other aspects of visual changes under +G_z, alternative endpoints might be able to overcome some of the limitations of PLL. To this end the authors have designed an endpoint which uses a foveal target based on previous findings that central lights at set brightness above +1 G_z detection thresholds disappeared with increasing +G_z,[9] and that the required difference in luminance between two light sources increased under +G_z.[2] The parameters of this stimulus, including size, orientation, and spatial and temporal frequency were tested and refined in a pilot study. This confirmed its function as a usable endpoint with a small number of subjects ($N = 4$). The aim of the present study was to test the applicability of this stimulus as an endpoint for a larger sample size across a range of acceleration exposures and to describe its character using PLL as a reference point.

METHODS

Subjects

Volunteering to participate in the study were 12 healthy subjects (4 women, median age: 32 yr, age range: 23–48 yr, height: 1.8 ± 0.09 m, weight: 81.6 ± 11.7 kg; unless otherwise stated, values are mean ± SD). Subjects underwent medical screening to identify any exclusion criteria (history of significant cardiac, vascular, pulmonary, neurological or endocrine disease, spinal injury, medication use, or pregnancy), 12-lead ECG, and urinalysis. Normal vision was confirmed for all subjects via a Snellen chart for visual acuity (≥ 6/6 bilaterally, with correction worn as required) and a Pelli Robson chart for contrast sensitivity (>1.5 at both 1 m and 3 m) and subjects with any history of eye pathology, trauma, or surgery were excluded. None of the subjects were fast-jet pilots or were routinely exposed to high G outside of centrifuge research. All subjects undertook between three and five familiarization sessions to achieve confidence and competence using both old and new endpoints and, if required, G-suit inflation. The final familiarization session took place less than 24 h before the first trial run. To minimize any potential remaining effects of a G layoff, a G warm-up (see below) preceded each trial run. The study protocol was approved by the UK Ministry of Defense Research Ethics Committee (MODREC 2002/MODREC/20). Written informed consent was obtained from all subjects and the study was conducted in accordance with the principles of the Declaration of Helsinki.

Equipment

The study was performed on the RAF High G Training and Test Facility (HGTTF) human centrifuge using a representative Eurofighter Typhoon gondola and seat (arm length: 7.5 m, seatback angle: reclined 22° from vertical, accelerometer axis: gondola vertical, accelerometer position: head level). Subjects were harnessed into the seat wearing an RAF flight suit and full coverage anti-G trousers (FCAGT) fitted by qualified survival equipment technicians. An additional padded seatback and headbox cover were used to minimize vibration. The right armrest housed a button under the right thumb which, if pressed, ended the acceleration exposure ("end" button). Participants held a marker button which activated a square wave voltage pulse. All data, including centrifuge acceleration, were recorded at a sample rate of 200 Hz using LabChart v8 (ADInstruments, Sydney, Australia). A live video feed was monitored by a qualified centrifuge Medical Officer for signs of impending G-LOC or medical criteria for termination.

The PLL endpoint used a custom-built lightbar with red LEDs flashing at 1 Hz positioned to subtend a 30° arc on either side of the center point of the bar. The endpoint was defined as when a subject fixating straight ahead lost clear vision of the peripheral LEDs, with the level of +G_z recorded at this endpoint denoted as PLL. The assessed grating-based visual endpoint consisted of a small (7–9° arc) single foveal stimulus consisting of a high spatial frequency (6–7 cpd depending on selected test parameter set) sine wave grating with Gaussian filter, oriented at 45° to the vertical, presented on a midtone gray background (**Fig. 1**). The contrast between the white and black bars was set at 4%. The orientation of the stimulus flipped across the vertical axis by 90° every 500 ms (2 Hz). The accuracy of timings was ensured via automated checks of monitor refresh rate prior to presentation of the stimulus. The stimulus and GUI were programmed with Python (v3.9, Python Software Foundation,

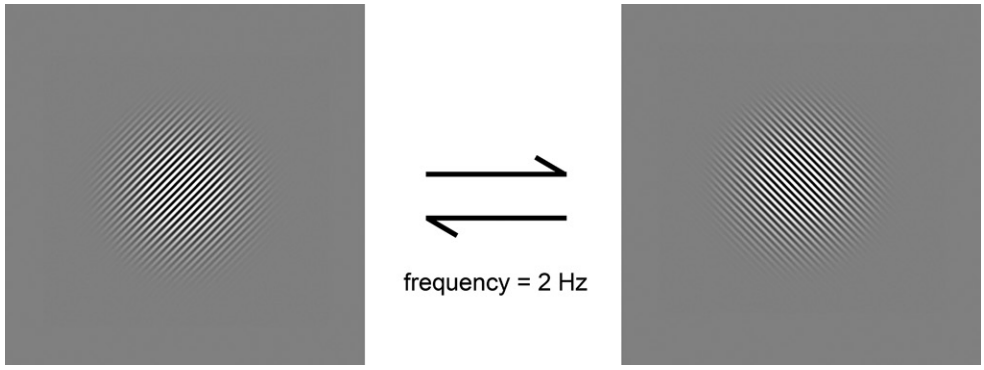

Fig. 1. The central stimulus employed by the Grating Loss endpoint (GL) demonstrates changes in orientation. Contrast in this example is artificially elevated for reproduction. All parameter sets operated with 4% contrast during testing.

Wilmington, DE, United States) using visual stimuli modules from PyschoPy3 (PsychoPy, Nottingham, United Kingdom).[18] The test was displayed on a 17.3″ portable monitor (GST173, G-STORY, Dongguan, China; resolution: 1080 p, refresh rate: 165 Hz, response time: 1 ms, contrast ratio: 1000:1, brightness setting: 50%) mounted centrally above the light bar. The program was driven by a laptop graphics card (Radeon HD 7970M, Advanced Micro Devices Inc., Santa Clara, CA, United States) connected to the monitor via USB-C.

The endpoint was defined as the point where the white and black lines of the grating were no longer distinguishable from the background screen (grating loss; GL). General dimming around the corners of the screen was permitted so long as this did not encroach upon the stimulus. Ambient gondola lighting was turned off throughout the study to minimize variations in illuminance. During the pilot trial, there was no difference in screen luminance ($45.5 \pm 1.7\,cd \cdot m^{-2}$) and background illuminance at eye level ($6.31 \pm 0.4\,lx$) at the start and end of each day and, therefore, these were not recorded during the current trial.

During the pilot study, it was found that the endpoint could be made clearer for individuals by minor adjustments in stimulus size and spatial frequency of the grating. Thus, four parameter sets were created (Set A = 7° arc, 6 cpd; Set B = 8° arc, 7 cpd; Set C = 8° arc, 6 cpd; Set D = 9° arc, 6 cpd). All participants started with Set A in the first familiarization session. For subsequent runs, the default set was that which was used successfully by the subject in the previous session. If, during the G warm-up runs, the subject was unable to identify the visual change, then a different parameter set was selected. The set used in each session was recorded.

Procedure

A total of six centrifuge sessions were completed over 3 d of testing. On two of the days, the first session consisted of gradual acceleration onset runs (GOR:1 and GOR:2). The remaining sessions consisted of rapid acceleration onset runs (ROR), each producing a single PLL and a single GL determination. Subjects remained relaxed throughout all centrifuge exposures but were permitted to perform muscle tensing if required following termination of the run via activation of the end button, which returned the centrifuge to baseline (+1.6 G_z). Prior to data collection in all sessions, three to four runs were performed to allow physiological adaptation to +G_z (G warm-up) and to identify and confirm the clearest parameter set for the GL for that session. These runs were identical to the GOR profile and conducted with FCAGT deactivated.

GOR sessions ($0.1\,G \cdot s^{-1}$) consisted of a G warm-up, followed by six runs with the anti-G valve (and hence FCAGT) turned off (GOR-Off) and six runs with the valve turned on (GOR-On). A 1-min break was taken at baseline between each run. A longer break (approximately 5 min) was taken between GOR-Off and GOR-On to allow adjustment and confirmation of anti-G valve function. Both PLL and GL endpoints were assessed in all runs. Participants were instructed to focus on the GL stimulus, ensuring the red lights were visible in the peripheral vision. Upon reaching the GL endpoint, the marker button was pressed. Acceleration continued until the PLL endpoint occurred, at which point subjects pressed the end button. The acceleration at which the marker was pressed was recorded as GL and the point when the stop button was pressed was recorded as PLL.

Rapid onset sessions consisted of a G warm-up, followed by ROR ($3\,G \cdot s^{-1}$) to a target plateau, which was held for 10 s. All runs were completed with the anti-G valve on and FCAGT activated. The initial plateau was 0.8–1 G_z below the average G threshold determined in the preceding G warm-up runs. If the selected endpoint was not replicated, the target +G_z was increased by 0.2 to 0.4 G_z until the endpoint was reached (as signaled by subject activation of the end button). Where required, bracketing either side in 0.2-G_z intervals was performed to confirm the threshold measure. Determinations of PLL and GL were made independently in ROR serials, with the order of determination balanced across the repeats. If a threshold determination could not be reached in a maximum of six runs, the result was marked as nondetermined.

At the end of each serial, subjects were asked to score the ease at which each endpoint was identified on a scale of 1–10 (1 being impossible, 10 being extremely easy). As GOR-Off and GOR-On were performed in the same serial, results were only separated into GOR and ROR conditions. The GL parameter set used by each subject for each session was recorded.

Data Analysis

Descriptive statistics were used to assess the average values and variability for each endpoint across three conditions: GOR-Off, GOR-On, and ROR. Test–retest reliability was assessed via intraclass correlation (ICC) using a two-way random model with measures of absolute agreement (ICC A,k).[21] ICC values can be grouped into ranges of <0.5, 0.5–0.75, 0.75–0.9, and >0.9, indicating poor, moderate, good, and excellent reliability, respectively.[11]

For the GOR conditions, a 2-way repeated measures ANOVA was performed (following assessment of normality) to assess the effect of condition (GOR-Off vs. GOR-On) and the endpoint used (GL vs. PLL) on the +G_z level reached. GL and PLL results in the ROR condition were compared using a paired *t*-test. Equality of the variance in results for GL and PLL were compared for each condition using Levene's test. Between-session variability was assessed for each endpoint in the GOR-Off and GOR-On conditions, with a paired *t*-test between GOR-1 and GOR-2. Analysis of GOR conditions was otherwise performed on data from GOR-1 alone to remove the influence of between-session variability on these results. Pearson's correlation and linear regressions were employed to compare GL and PLL results for each condition. Subjective endpoint scores were assessed using Friedman's test. All statistics were performed using IBM SPSS Statistics v.22 (Chicago, IL, United States) and significance was set at $P < 0.05$. All values are presented as mean ± SD, unless otherwise stated.

RESULTS

One subject withdrew from the study due to centrifuge-related nausea during familiarization and is excluded from analysis. The remaining 11 participants completed the trial without incident. Of the participants, 82% ($N = 9$) required only one GL parameter set for all runs. Four of these used Set B throughout, three used Set D, and one used Set A. One individual used either Set B or C (1 cpd variation in spatial frequency) in all runs. The remaining individual used set A for GOR-1 and GOR-2, but used sets B, C, or D for ROR. Descriptive data for the GOR-1 serial are presented in **Fig. 2**. There was a main effect of endpoint used [$F(1, 10) = 87.38$, $P < 0.001$] and of GOR condition [$F(1, 10) = 65.91$, $P < 0.001$] and a positive interaction between endpoint test and GOR condition [$F(1,10) = 17.44$, $P = 0.002$]. In the GOR-Off condition, mean GL was 0.28 G_z lower than PLL ($P < 0.001$). For GOR-On, GL was 0.46 G_z lower than PLL ($P < 0.001$). Results of Levene's test indicated that the variance with each endpoint was equal for both GOR-Off [$F(1, 127) < 0.001$, $P = 0.997$] and GOR-On [$F(1124) = 0.59$, $P = 0.442$]. +G_z acceleration was higher in GOR-On compared to GOR-Off by 0.87 G_z at GL ($P < 0.001$) and 1.1 G_z at PLL ($P < 0.001$).

In the GOR-Off condition, ICC for GL was 0.987 with a 95% confidence interval (CI) from 0.968–0.997 [$F(8,40) = 84.71$; $P < 0.001$] and for PLL was 0.986 with a 95% CI of 0.965–0.996 [$F(9,45) = 95.66$; $P < 0.001$]. ICC for GOR-On for GL was 0.986 with a 95% CI of 0.958–0.997 [$F(7,35) = 122.66$; $P < 0.001$] and for PLL was 0.981 with a 95% CI of 0.935–0.996 [$F(7,35) = 111.10$; $P < 0.001$]. Intraclass correlation, therefore,

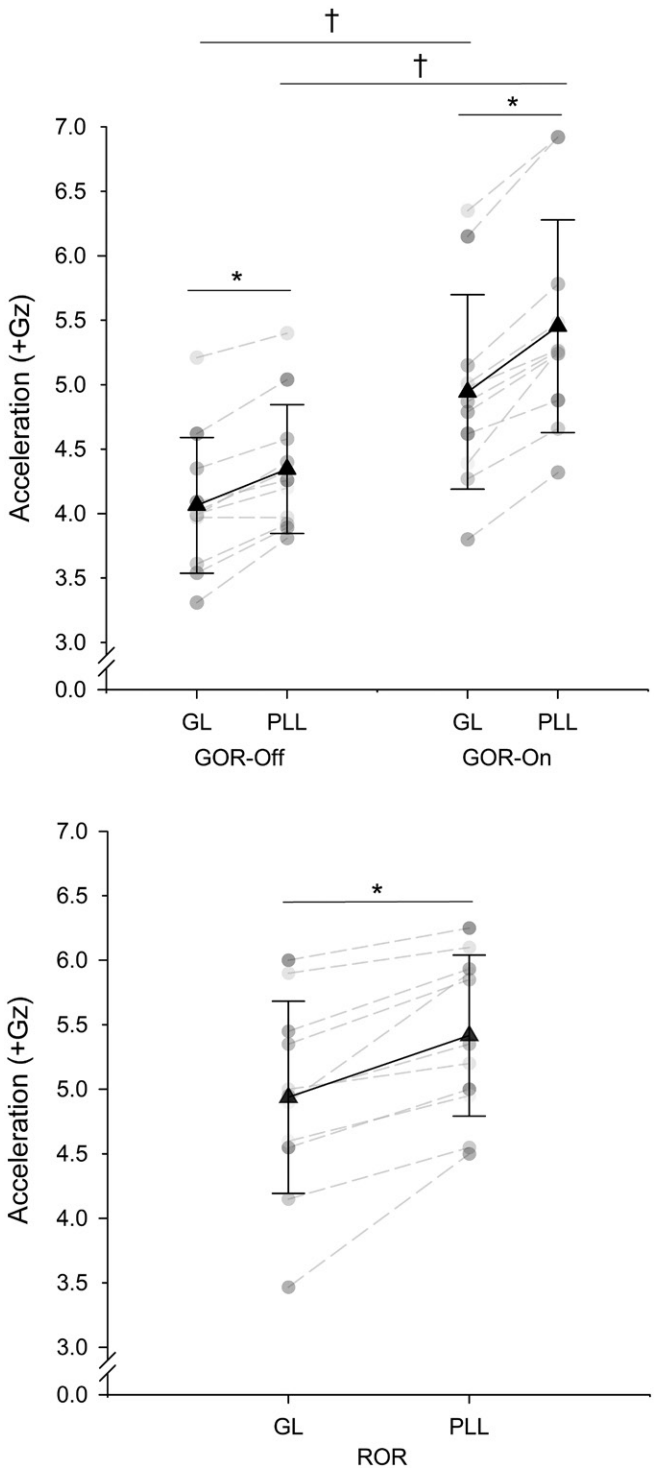

Fig. 2. Mean (SD) +G_z reached at the endpoint provided by each test (GL and PLL) during the first gradual onset session (GOR-1) with anti-G suits deactivated (GOR-Off) and activated (GOR-On), and for rapid onset runs (ROR; anti-G suit activated). *Indicates significant ($P < 0.001$) difference between the level of +G_z at GL and PLL. †Indicates significant difference ($P < 0.001$) in the level of +G_z between GOR-Off and GOR-On conditions with the same endpoint.

indicated "excellent" test–retest repeatability within session for both endpoints in both GOR conditions.

In the GOR-Off condition, there was a statistically significant between-session difference (GOR-1 vs. GOR-2) for both GL [$\Delta = 0.08\ G_z$, $t(54) = 2.45$; $P = 0.018$] and PLL [$\Delta = 0.08\ G_z$, $t(62) = 2.47$; $P = 0.016$]. In GOR-On, there was no significant between-session difference for GL [$\Delta = 0.02\ G_z$, $t(57) = 0.61$; $P = 0.546$] or PLL [$\Delta = 0.95\ G_z$, $t(60) = 1.95$; $P = 0.056$].

In the ROR condition, mean GL was 0.48 G_z lower than PLL [$t(10) = -5.56$; $P < 0.001$]. Levene's test signified equal variance with each endpoint [$F(1,82) = 0.02$, $P = 0.904$]. Intraclass correlation indicated "excellent" between-session test–retest repeatability for both endpoints. ICC for GL was 0.922 with a 95% CI of 0.796–0.978 [$F(9,27) = 12.08$; $P < 0.001$], and for PLL was 0.915 with a 95% CI of 0.757–0.979 [$F(8,24) = 15.81$; $P < 0.001$].

There was very strong correlation between GL and PLL in the GOR-Off [r(9) = 0.964, $P < 0.001$], GOR-On [r(9) = 0.975, $P < 0.001$], and ROR [r(9) = 0.928, $P < 0.001$] conditions (see **Fig. 3**).

Subjective endpoint rating results (0–10 scale) are detailed in **Table I**. Friedman's test showed no statistically significant difference in outcome rating across the conditions [$\chi^2(5) = 8.342$, $P = 0.138$].

DISCUSSION

This trial investigated the potential application of a computer-generated contrast grating as a visual endpoint for centrifuge research. For the 11 individuals tested, GL proved to be a reliable and repeatable method to measure G tolerance. Repeated measures for individuals showed small variability (mean SD: GOR-Off = ±0.14 G_z, GOR-On = ±0.25 G_z, ROR = ±0.29 G_z), with excellent test–retest repeatability (ICC 0.922–0.987). Despite using a foveal stimulus, GL was consistently reached before PLL (0.3–0.5 G_z, depending on FCAGT use and condition).

For both endpoints, the within-subject variance (SD) for repeated measures during a session was ±0.14 G_z for

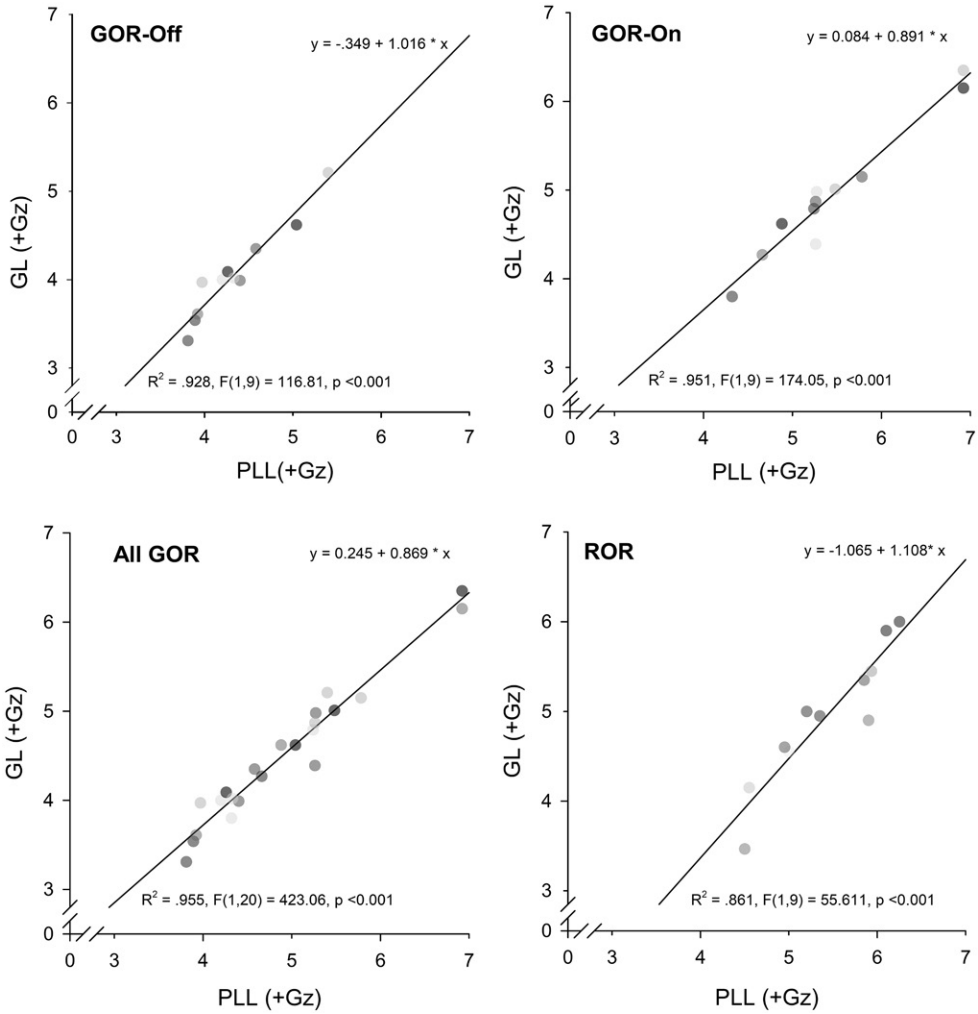

Fig. 3. Linear regression plots for each GOR condition separately, both GOR conditions combined and ROR. All regression lines are significant to a value of $P < 0.001$.

Table I. Results of the Subjective Feedback Questionnaire.

	GOR		ROR		COMBINED	
SCORE	**GL**	**PLL**	**GL**	**PLL**	**GL**	**PLL**
Mean score (SD)	6.4 (1.8)	6.9 (1.8)	6.5 (1.6)	7.2 (2.0)	6.5 (1.7)	7.1 (1.9)
Min score	3	3	3	1	3	1
Max score	9	9	9	9	9	9

Values represent results on a 1 to 10 scale, with 10 signifying that it was "extremely easy" to identify the endpoint and 1 signifying that the endpoint was "impossible" to identify.

unprotected GOR and ±0.25 G_z for protected GOR. However, the SD of between-subject measures was ±0.5 G_z unprotected (both endpoints) and ±0.8 (GL) to ±0.9 G_z (PLL) protected. This indicates that subjective visual endpoints remain useful when assessing within-subject effects (e.g., different anti-G suits), but may be less reliable for between-subject assessments. It is unclear to what extent this is due to true interindividual difference in head-level oxygenation under +G_z or the endpoint itself.

This study further highlights the importance of defining which endpoint has been used in trials or equipment evaluations to determine G tolerance. As both GL and existing endpoints like PLL and CLL use different stages of visual changes under +G_z, the acceleration level reached at the endpoint will differ. Comparisons between studies or equipment may, therefore, be invalid if different endpoints are employed. This is also the case where parameters of PLL such as peripheral light location and brightness are changed.

Typically, visual changes under acceleration are considered to occur initially at the periphery, progressing centrally,[1,10] with this pattern thought to be related to the anatomical distribution of the retinal blood supply. That the foveal GL was routinely reached before PLL is counter to this working model. However, it has previously been observed that when a foveal light is of low luminance (0.2 log units above detection threshold at +1 G_z), it can disappear at as low as +1.4 G_z.[9] The required luminance to identify a light increases twofold at +3 G_z and threefold at +4 G_z,[27] suggesting perceived "light loss" under +G_z may occur due to a threshold shift in sensitivity to visual stimuli rather than absolute retinal failure.[28] In support of this hypothesis, it has been reported that sufficiently bright foveal lights can be sensed despite individuals reporting "blackout,"[8] with electroretinogram activity and consensual light reflexes persisting past CLL.[15]

The upward threshold shift has been noted to be greater in the peripheries than at the fovea[27] in a similar manner to that seen with hypoxic hypoxia.[7,24] Therefore, where stimuli across the visual field are of similar intensity (as with ambient lighting or the traditional light bar), the threshold is reached at lower levels of +G_z in the periphery than at the fovea, resulting in the classic appearance of tunnel vision. The GL endpoint, however, presents a central stimulus that is closer to threshold at +1 G_z. Therefore, a smaller increase in +G_z acceleration was needed to make it undetectable than the stronger stimulus of the peripheral lights.

Selection of the GL stimulus was based on the findings described above, whereby the difference in luminance required to distinguish a background and a target light increases with higher levels of acceleration (i.e., a "differential luminance threshold shift").[2] As similar changes are noted when breathing hypoxic gas mixes at +1 G_z,[6] it is likely that the effect is due to reduced oxygen delivery to the retina. The GL grating emulates the stimulus used in the earlier studies such that a low differential luminance between the light and dark bars and the gray background of the screen ensures that the stimulus is identifiable at +1 G_z but becomes indistinguishable from the background under acceleration when the differential luminance threshold is increased.

While this trial employed a stimulus classically used for contrast sensitivity assessments, it was not designed as an assessment of contrast sensitivity under +G_z. Previous studies have shown that sensitivity to contrast gratings may be affected following +G_z exposure,[3] but the authors are unaware of any previous studies highlighting this during the +G_z exposure itself. Further research specifically designed to study the impact of +G_z acceleration on foveal and peripheral contrast sensitivity may prove useful to identify whether the interpretation of visual displays in aircraft might be affected, and to help set requirements for contrast settings in these devices if required.

Using PLL as a reference, GL performed similarly to currently used endpoint measures. During this trial, PLL showed a slightly higher, but still small, variability in repeated measures for each individual (mean SD: GOR-Off = ±0.14 G_z, GOR-On = ±0.23 G_z, ROR = ±0.34 G_z), and similarly "excellent" test–retest repeatability (ICC 0.915–0.896).

Compared with previous studies, PLL performed better as an endpoint than expected.[5,16] The instruction for subjects to use their own unique but consistent endpoint, rather than relying on complete loss of the peripheral lights, may explain the improved intraindividual performance of PLL found in this study. This approach may result in a wider interindividual variability but provides an alternative method to improve repeatability where pairwise comparisons are used.

Both endpoints scored between 6.4 and 7.2 in usability depending on condition, with no difference found in average scores. Individual subjects tended to prefer one test over the other. Informal comments noted that some found GL more distinct ("Much more of a dichotomy, it's either there or not", "Seems to be more definitive, i.e there/not there"), while others found the same for PLL ("Harder to find distinct endpoint [with GL] than PLL", "[GL] was a bit harder [than PLL]"). This is reflected in the ratings scores. For those who gave a low score to one endpoint (N = 7), all but one gave high scores for the other, while the remaining subject gave low scores for both.

While GL may overcome some of the potential downsides of PLL, it introduces different challenges. Titration of the parameters of the GL stimulus was sometimes required to make the endpoint clearer for certain individuals. However, during this trial, 82% of participants were able to use the same test parameter set throughout, with only two participants requiring readjustment during the G warm-up period between sessions. While this may slightly increase intraindividual variability, the differences between parameters were small and variance remained similar to PLL. Within-subject variance was similar for individuals who changed sets to those who used the same throughout. There is also a possible effect on recorded GL for participants with reduced contrast sensitivity, which is not routinely screened for in aircrew medical assessments. Due to the similar contrast sensitivities of participants in this study, the effect of individual variation in contrast sensitivity was not assessed. The study design did not investigate the effect of biological sex or age, or other visual conditions, and these would require separate consideration.

Following experience in the pilot study, subjects were instructed to determine their own reproducible endpoint when using PLL, rather than relying upon absolute loss of the peripheral lights. For GL, subjects were required to use a single specific endpoint. If the same approach used with PLL was employed with GL, individual variability may have been reduced further for this endpoint. Further, despite the use of FCAGT, participants did not reach particularly high levels of +G_z. It is at higher levels of acceleration (+7–9 G_z) where anecdotal evidence suggests the PLL endpoint is less accurate, and a dedicated study looking at higher acceleration levels may reveal greater differences between the endpoints. The lighting conditions in the gondola varied slightly between the GOR condition and the ROR condition, as only one test was active for ROR runs, whereas for GOR the endpoints were assessed simultaneously and hence two light sources (light bar and GL display screen) were active. While this does not affect the results within the condition, it limits direct comparison between GOR and ROR thresholds in this trial. Finally, while vibration was minimized in the gondola with additional padding, it was not able to be removed entirely and may have affected identification of the grating close to GL.

This initial investigation demonstrates that GL is a usable and repeatable endpoint. Further studies with greater numbers are required for complete validation and to assess potential variances with biological sex, age, and differences in visual acuity. The findings of this study suggest potential applications of GL to complement PLL as a centrifuge research endpoint. The lower +G_z acceleration experienced at GL compared to PLL endpoints may offer new opportunities to centrifuge researchers. In trials with multiple exposures, the lower level of acceleration may reduce subject fatigue and motion symptoms. Where performance of a G-protection solution at a specific target +G_z is being tested, use of PLL only assures that aircrew will not experience loss of the visual field to 60°, which is unlikely to be acceptable in flight. If a GL endpoint is used, a potentially safer acceleration limit can be provided at approximately 0.3–0.5 G_z below where this unacceptable degree of visual impairment would occur.

GL may also offer additional benefit as a supplementary endpoint. Given the separation of GL and PLL, both endpoints can be employed simultaneously, as in the GOR serials in this trial. By employing a stepwise increase in rapid onset runs, it has since been possible to employ both endpoints in a single ROR test serial. This provides two separate data points on which to align all subjects and compare physiology. Concurrent use of both endpoints may hence help to increase our understanding of physiology and performance at lower levels of +G_z than traditionally assessed.

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