The influence of whole-body vibration, media, and artificial lighting on eye-movement during reading

A influência da vibração de corpo inteiro, da mídia e da iluminação artificial no movimento dos olhos durante tarefas de leitura

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ABSTRACT

Objective: To evaluate if participants, subjected to whole-body vibration, two different types of media (paper *versus* tablet) and two lighting environments (fluorescent *versus* LED), present a difference in eye-movement parameters during reading tasks.

Methods: Fourteen adults silently read two different texts in each one of the eight randomized testing conditions (whole-body vibration *versus* media *versus* lighting), resulting in 16 different texts read per individual. Whole-body vibration was applied in the vertical direction, 5Hz and 0.8 m/s^2 root-mean-square amplitude, a condition similar to those experienced by forklift truck drivers. Participants were in a sitting position with a backrest. An eye-tracker evaluated the eye-movements during the reading task.

Results: Whole-body vibration significantly reduced the number of ocular fixations, and cross-correlation; and increased the reading efficiency, fixation duration, directional attack, and binocular anomalies. Neither the type of media nor the lighting environment interfered significantly with the eye-movements, both in situations with and without vibration.

Conclusion: The results indicate that whole-body vibration interfered in the eye-movements during the reading task. This may impose a difficulty to process the visual information and to synchronously coordinate the binocular movements under vibration environments.

RESUMO

Objetivo: Avaliar se participantes submetidos à vibração de corpo inteiro, a dois tipos diferentes de mídia (papel *versus tablet*) e a dois ambientes de iluminação (fluorescente *versus* LED) apresentam diferença nos parâmetros de movimento dos olhos durante tarefas de leitura.

Métodos: Quatorze adultos leram silenciosamente dois textos diferentes em cada uma das oito condições de teste (vibração de corpo inteiro *versus* mídia *versus* iluminação), de forma aleatória, resultando em 16 textos diferentes lidos por indivíduo. A vibração de corpo inteiro foi aplicada no sentido vertical, com amplitude de 5Hz e 0,8m/s^2 da raiz do valor quadrático médio, em condição semelhante às vivenciadas pelos motoristas de empilhadeiras. Os participantes permaneceram em postura sentada com encosto. Um rastreador ocular avaliou os movimentos oculares durante a leitura.

Resultados: A vibração de corpo inteiro reduziu significativamente o número de fixações oculares e a correlação cruzada entre os olhos e aumentou a eficiência de leitura, duração da fixação, ataque direcional e anomalias binoculares. Nem o tipo de mídia nem as condições de ambientes de iluminação interferiram significativamente nos movimentos oculares, tanto em situações com ou sem vibração.

Conclusão: Os resultados indicam que a Vibração de Corpo Inteiro pode interferir nos movimentos oculares durante a leitura. Isso pode impor uma dificuldade no processamento da informação visual e na coordenação síncrona dos movimentos binoculares em ambientes de vibração.

INTRODUCTION

Whole-body vibration (WBV) occurs when a body supported by a vibrating surface (and not just part of it) is subjected to oscillations throughout the body.[1] Almost every environment produces enough mechanical vibration to cause effects on the complex and dynamic structure of the human body. Different WBV parameters, such as frequency, amplitude, direction, duration, posture, and transmissibility of the contact surface, may degrade body functions, including visual perception, with an impact on health, comfort, and/or task performance.[1,2]

Whole-body vibration transmitted through the body to the head, referred to as seat-to-head transmissibility (STHT), and through the head to the eyes, can affect essential voluntary and involuntary eye-movements during reading.[3] The influence of WBV may be more pronounced when considering reading ability, as it requires overly complex visual and cognitive-motor activity. Reading depends on internal (for example, integrity and alignment of the binocular system, visual field amplitude, foveal image stability) as well as external factors (for example, vibration environment, type of media, lighting).[4,5]

A study evaluated aircraft pilots who were submitted to different frequencies (3Hz to 21Hz) in the vertical direction (Z-axis) and identified that, in general, the worst results while performing reading, typing and writing occurred below 9Hz.[6] Another study investigated the vestibular ocular reflex under unidirectional translational WBV without head restriction, for a frequency range between 0.7 to 10Hz, with results suggesting that the degraded vision in WBV environments may be attributed to jerky head movements.[7] Train passengers, submitted to stationary lateral sinusoidal vibrations in nine discrete frequencies from 0.8 to 8.0Hz, reported a greater difficulty while reading and writing leaning over a table than while leaning against backrest, with the frequencies up to 5Hz having a particular influence on the perceived difficulty.[8]

Therefore, due attention is necessary when evaluating WBV effects in relation to position and WBV exposure direction. Fore-and-aft (X-axis) and lateral (Y-axis) WBV are known to influence reading more than vertical vibration (Z-axis), causing more reading errors.[9] However, when the reader was in a sitting position with a backrest, an amplitude increase caused more visual degradation in fore-and-aft directions. In vertical and lateral directions, more visual degradation occurred with no backrest.[10] Moseley and Griffin showed that vertical vibration may worsen the reading performance of subjects seated with no backrest at frequencies from 0.5 to 5Hz and at different amplitudes.[11]

In addition to WBV, the human body responds to other aspects of the environment, such as the type of media and environment lighting. In the current digital age, classic books written with ink on soft paper have primarily been replaced by electronic media, with high resolutions and backlit liquid-crystal displays (LCD), which may trigger higher visual fatigue.[12] Moreover, the human visual and circadian physiology evolved adaptively to the wide sunlight spectrum. Natural light emits different wavelength frequencies than artificial light.[13] However, artificial lighting is omnipresent in people's daily lives since environment illumination and electronic equipment (among other examples) use it. Thus, it is expected that long exposure periods to artificial light can cause headaches, eye fatigue, skin problems, and can affect work performance and humor.[14,15]

Although reading speed, visual fatigue and reading comprehension are parameters usually used to evaluate the reader's performance, they have a considerable degree of subjectivity and may not detect the influence of WBV, difference in the type of media and of lighting. However, computerized evaluation of eye-movements with an eye-tracker during reading may be a sophisticated solution, as it can quantify a range of parameters not measured manually, that have little conscious control, as such control is mostly subcortical.[16,17]

The objective of this study is to evaluate whether participants, subjected to WBV, two different types of media (paper *versus* tablet) and two lighting environments (fluorescent *versus* LED), present a difference in eye-movement parameters during reading tasks. Although these different physical agents are present in people's daily lives, the combined evaluation of these variables on reading is new. Research is important to gain a better understanding of their influence and in the study of eye-movements itself. Moreover, the WBV assembly is relevant for occupational and educational health, as the physical agents used are similar to situations when a subject is vibrating inside a means of transport and the object is outside, such as when forklift truck drivers need to read something on a shelf.

METHODS

Participants

Fourteen volunteers took part in this prospective and randomized research (mean age: 28.8±7.8 years; 43% males). The participants were Portuguese native speakers, chosen by convenience, assessed at random. All participants had normal or corrected-to-normal visual acuity. They were healthy at the time of the tests, and met the exclusion criteria for

WBV testing defined by international standards.[18] Whole-body vibration amplitudes and duration safety values, for the frequency range of interest, were well below those established by the European Parliament.[19] All participants signed the informed consent to be included in the study. All study procedures were approved by the Research Ethics Committee of the Universidade Federal de Minas Gerais (CAAE: 55476015.7.0000.5149), which were performed in full accordance with the Declaration of Helsinki.

Whole-body vibration platform

The WBV platform assembly consisted of a wooden chair with a backrest and metallic feet, positioned on a supporting plate (700 x 1,000 x 3mm of steel with folded edges) (Figure 1). Four 1020 steel compression springs supported the plate to allow for vertical movement. The springs had nine coils of 76mm external diameter, 350mm height, and 6mm wire diameter. Polyvinyl chloride tubes (PVC) guided the springs. The tubes were placed inside the springs that, in turn, were placed in a steel tube welded to the metallic base of the platform.

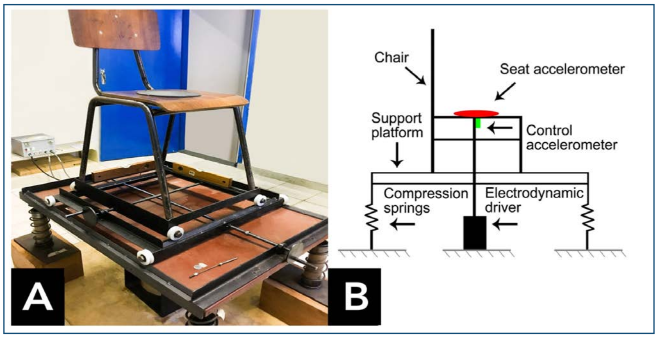


Figure 1. (A) Photograph of the Vibration Platform Assembly used for the WBV Tests, and (B) schematic representation.

Vibration levels were measured on the chair seat to overcome the dynamics of the platform. An electrodynamic shaker (Table 1), powered by a power amplifier, applied the desired sinusoidal excitation. The vibration assembly, together with a metal push rod attached both at the shaker and at the vibrating platform, guaranteed the main acceleration for the participants at the vertical direction (Z-axis) and reduced excitation at the fore and aft (X-axis) and lateral (Y-axis) directions.

A metallic guide between the chair and the plate guaranteed that the center of mass of the participant coincided with the center of the shaker. The guide was developed with screws in each direction to allow for easy adjustment. Two bubble levels were used to guide the above-mentioned procedure.

Table 1. Measurement system, composed by excitation, data acquisition, and control systems

	Equipment	Model	Manufacturer
Excitation System	Power Amplifier	CE 2000	Crown
	Electrodynamic driver (Shaker)	VTS 150	Dynamic Solution
Data Acquisition System	Triaxial Accelerometer (at the head)	Deltatron Type 4524-B-001	B&K
	Triaxial Accelerometer (at the chair)	AP2083	APTechnology
	Four-channel FFT Analyzer	Photon II	LDS Dactron
	Four-channel Digital Analyzer	Maestro®	01-dB
Control System	Control Board	Model 1104	dSPACE
	Uniaxial Control Accelerometer	325A	PCB Piezotronics
	Signal Conditioner	482A22	PCB Piezotronics

To study the influence of WBV during reading tasks, the first step is to decide which parameters to be used in the evaluation. ISO2631-1 standard[20] presents several forms of measuring and evaluating vibration on the human body. WBV amplitude complexity may result in peak values at certain instants of time that do not repeat or may not be significant at others. Therefore, the mean weighted acceleration value (*aw*) is generally used for the exposure evaluation, as some frequencies are less important to the total value than others.[1] The calculation is performed using the root-mean-square (RMS) response, which is the square root of the squared mean weighted acceleration value, calculated according to Equation 1.

$$a_w = \left[\frac{1}{T} \int_0^T a_w^2(t)dt \right]^{\frac{1}{2}} \qquad \text{(Equation 1)}$$

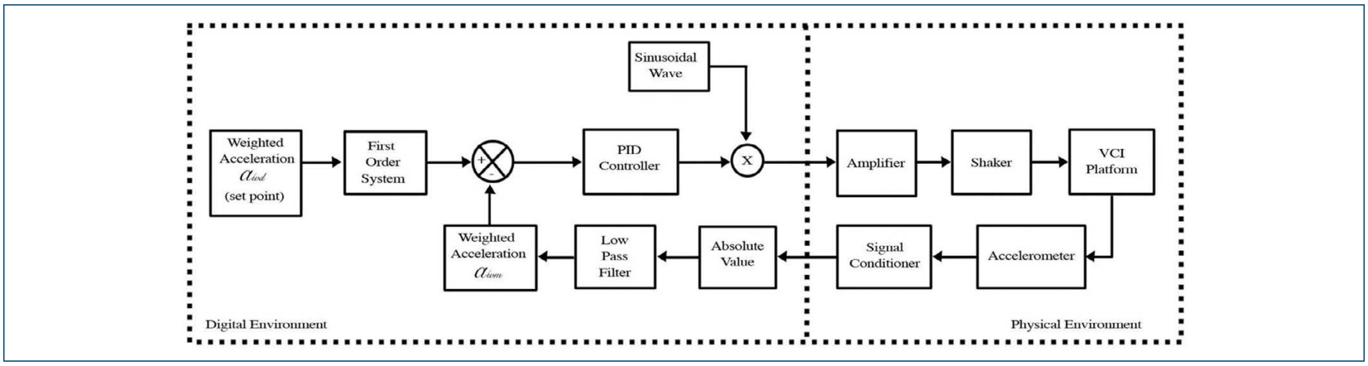
where (a_w) is the weighted acceleration value in m/s², $a_w(t)$ is the weighted acceleration as a function of time in m/s² and t is the measurement duration in seconds.[20]

Equation 1 is the parameter evaluation option when the crest factor is less than 9. The crest factor is the ratio between the maximum a_w present on the time signal to the average RMS value for the duration of interest.

Data acquisition systems

Table 1 presents the components of the measurement system, composed of both data acquisition and control systems (apart from the excitation system). The data acquisition has two triaxial accelerometers, as well as two four-channel analyzers (one of them being a fast Fourier transform [FFT] analyzer). The control system has one uniaxial accelerometer with a signal conditioner and a control board.

Attached to the volunteer's heads, using rubber bands, the first triaxial accelerometer monitored the head's movement. Placed on the chair, the second triaxial



PID: Proportional integral derivative; VCI: Vibração de corpo inteiro [Whole-body vibration].

Figure 2. Diagram of the digital and physical environments of the Control System

accelerometer measured the three axes of vibration felt by the volunteers at the first contact point, as recommended by the International Standard.[20] The uniaxial accelerometer (placed under the chair) was used to confirm that the desired excitation level sent to the volunteer was accurate. A control system was developed to correct the level, if necessary. However, due to the system limitation (e.g., number of channels available), only the vertical direction (Z-axis) was monitored by the control system.

The LDS Photon II system was responsible for data recording from both the uniaxial accelerometer (used in the control system) and the triaxial accelerometer placed on the volunteer's head. The 01-dB Maestro® system was responsible for measuring the weighted acceleration from the triaxial accelerometer placed on the chair, although it was used mainly as a verification of the control system at the Z-axis.

Control system

The instruments used in the control system to monitor the vertical direction are shown in table 1 and figure 2. A control algorithm, developed in-house for the dSPACE 1104 control board system, maintained constant vibration of the platform.[21] The system controlled the acceleration measured by the uniaxial accelerometer that was transformed in weighted acceleration using a digital filter system, according to the ISO2631-1 standard.[20] The weighted acceleration was compared to the acceleration specified by the platform operator and a Proportional-Integral-Derivative (PID) controller corrected the vibration amplitude.

Eye-tracking system

The ReadAlyzer system (Compevo AB, Stockholm, Sweden), used to quantitatively monitor eye-movements during reading tasks, consists of both hardware and software.[17] The former measures the eye movement, while the latter automatically analyzes the recording of these movements, converting the information into reading parameters, as shown in table 2. The ReadAlyzer hardware is composed of goggles without lenses, connected to a measuring unit, which is connected to a computer. The equipment illuminates each eye with two low-intensity infrared lights and measures the amount of reflected light as horizontal movements. The equipment-sampling rate is 1,200 times per second, with a mean value every 20 samples (that is, 60 means per second).

Table 2. Eye-movement parameters evaluated by the *ReadAlyzer* Software

Parameters	Definitions
1. Fixation	Number of left-to-right eye pauses per 100 words
2. Regression	Number of right-to-left eye pauses per 100 words
3. Reading Rate	Number of words read per minute
4. Fixation duration	Total reading time in seconds, divided by the number of fixations
5. Directional attack	Number of regressions, multiplied by 100, and divided by the number of fixations
6. Reading efficiency	Reading rate divided by the sum of Fixations and Regressions
7. Binocular Anomalies	Saccade events where both eyes are moving in opposite directions
8. Cross-correlation	Correlation of sizes of right and left eye saccades

Procedures of data collection-

Eight testing conditions were randomized between reading under WBV (with or without WBV at Z-axis, 5Hz, 0.8 m/s^2), media (sulfite paper or tablet), and artificial lighting (fluorescent or LED). Two texts were read under each condition (called here T1 to T8), totaling 16 texts read per participant. The entire battery of tests (16 texts read in total) lasted an average of 55 minutes per session. Texts were printed either on A4 white sulfite paper or shown on a tablet, Samsung S2 SM-T810 model (Android operating system 5.0 Lollipop, 9.7 inches screen, and 2048x1536 pixels resolution). Both media used black Times New Roman font, size 12 and 1.5 interline space. The paper and the tablet were fixed to a pedestal out of the vibration platform, ensuring reader vibration only. Eye-tracking goggles were aligned with the outside of each volunteer's pupils. Refractive correction was used when necessary. All volunteers read the text in silence.

Analyses of the influence of WBV on reading ability were conducted with individuals in the sitting position, at the z-axis, referencing the orthogonal coordinate system directions for mechanical vibrations in humans,[22] that is, vertical direction. The first point of contact between the human body and the source of vibration was used to position the transducers.[20] The parameter used to evaluate the vibration exposure was the RMS weighted acceleration expressed in m/s^2 rms. The weighting curves used in the analysis considered the position and posture of the vibrating individual.[20] Volunteers were asked to keep their backs supported against the backrest and their feet also supported, with no predetermined posture pattern required for hands, arms, legs, and head.

The testing room (white wall and ceiling, no window) was randomly lit by a compact fluorescent light (white, 25w, 220v, Philips) or by a compact white LED light (16w-100w E27 30000K 100v-240V, Philips). The lights were placed on a support with 1.80m height, out of the platform and to the right of the volunteer, positioned so that the light was on top of the text read. The mean distance between the eyes and the text was 56.2cm, from the eye to the light source was 47cm, and from the text to the light, it was 77.4cm. While the vibration setup was established and stabilized, volunteers remained seated with their eyes closed. The center of mass of each volunteer was adjusted to ensure that the shaker was in the middle of the platform.

Data analysis

Test conditions were compared using independent two-tailed samples for Student's *t* tests. The effect size was calculated (Cohen's *d* value) to determine the clinical significance of the differences. Results close to 0.20 were considered of little effect, 0.30 to 0.49 of moderate effect, and over 0.50 as having a large statistical effect.[23] The irrelevant difference among reading situations (two types of media and two types of lighting) allowed the merging of data without WBV, as well as data with WBV. The significance level was set at $p<0.05$.

RESULTS

The present study identified that WBV significantly affected different eye-movement parameters during reading (Table 3). Overall, WBV significantly reduced the number of fixations, and cross-correlation; and increased the reading efficiency, fixation duration, directional attack, and binocular anomalies ($p<0.05$). On average, WBV reduced the number of ocular fixations in 25%, from 100.6 to 75.4 fixations to read 100 words, with a strong effect size ($d=0.68$). Reading efficiency improved 17%, ($p<0.05$). The fixation duration became 32% longer, going from 0.35 to 0.46 seconds. There was an increase of 24% in the directional attack. The parameter of Binocular Anomalies worsened 164% ($d=0.82$), with a reduction of 16% in the cross-correlation ($d=0.51$). Both the number of ocular regression and the reading rate were the only parameters that did not have any significant difference between readings with and without WBV ($p=0.22$).

There was no media effect, as there was no significant difference between paper and tablet regarding eye movement while reading with nor without WBV ($p>0.05$). There was no lighting effect, as there was no significant difference in reading eye movements between rooms with fluorescent lights compared to LED lights, with nor without WBV ($p>0.05$).

DISCUSSION

This study aimed to evaluate if participants, subjected to WBV, two different types of media (paper *versus* tablet), and two lighting environments (fluorescent *versus* LED), presented a difference in eye-movement parameters during reading tasks. The WBV assembly was restricted to

Table 3. The effect of whole-body vibration on reading eye movement parameters

Reading eye-movement parameters	Without WBV (106 readings)		With WBV (104 readings)		Statistics (df = 209)			
	Mean	SD	Mean	SD	Δ	t	p value	d
Fixations*	100.6	41.0	75.4	32.3	-25%	3.55	0.0001	0.68
Regressions	17.4	12.7	15.4	11.4	-12%	0.88	0.222	0.17
Reading Rate (wpm)	202.7	74.2	216.3	75.4	7%	0.95	0.187	0.18
Reading efficiency*	7.9	3.6	9.2	3.2	17%	2.05	0.005	0.39
Fixation duration (sec)*	0.35	0.09	0.46	0.22	32%	3.47	0.0001	0.67
Directional attack (%)*	15.5	6.7	19.1	9.4	24%	2.34	0.001	0.45
Binocular Anomalies*	7.54	9.31	19.88	19.19	164%	4.25	0.0001	0.82
Cross-Correlation (%)*	78.2	19.6	66.2	28.5	-16%	2.63	0.0001	0.51

SD: Standard deviation; WBV: Whole-body vibration; Δ = Difference between with and without WBV; *df*: degree of freedom; *d*: Cohen's effect size; wpm: words per minute; * $p < 0.05$.

the vertical direction (Z-axis), 5Hz frequency, and 0.8m/s² RMS amplitude. These values were chosen after a literature review showed that the highest STHT transmissibility occurred at this frequency and this direction.[3]

According to the results of the current study, WBV caused significant changes in eye-movement parameters during reading tasks. In the absence of WBV, volunteers had 100.6 fixations to reading 100 words, whereas with WBV, it reduced to 75 fixations to read the same number of words. Fixations represent the total number of pauses that the eyes take to perceive the information more clearly, proportionally calculated per 100 words. Although not every word is directly fixated (short words with one to three letters are generally omitted, whereas longer words may be fixated more than once), all of them receive some kind of visual processing.[24]

The improvement of 17% in reading efficiency (reading speed divided by the sum of ocular fixations and regressions), under WBV, is mainly linked to the reduction in the number of fixations, as the number of regressions and the reading speed did not change. The increase of 24% in the directional attack (proportion of regressions when compared to fixations), under WBV, suggests that the reading was less fluent from left-to-right.

The increase of 32% in the fixation duration, under WBV, going from 0.35 to 0.46 seconds, was expected, as fewer fixations usually result in a longer duration, since these parameters are inversely proportional. These are evidence of greater difficulty in processing the current and previous information. The results with WBV may be a consequence of the reduced number of fixations, which increased the amount of information to be coded in the fovea and the time required to process a greater amount of information.

In a situation of WBV, the number of binocular anomalies increased 164%, with a large effect size (d=0.82), which represents that the eyes moved in opposite directions. Consistent with this result, under WBV, the cross-correlation between the eyes reduced 16%, with a moderate effect (d=0.51), indicating a difficulty to move both eyes synchronously. In reading tasks, the convergence of the eyes is required to support the binocular view of the text so that, for each fixation, the angle of convergence between two visual axes is adjusted to an accurate merging of two images in the retina,[25] allowing the axes to cross at the fixation point and to merge the binocular image.[26]

During typical reading, eyes are expected to have a slight difference of one letter at the fixation point, in addition to some cross-fixations.[27,28] For example, the left eye can fixate on one letter after the fixation point of the right eye, crossing fixations. Although the visual system tolerates a certain amount of disparity on the image projected on the retina, the increased number of binocular anomalies and the reduced cross-correlation after adding WBV may explain the constant reports of visual fatigue, nausea, and headache. Furthermore, the significant increase in binocular anomalies and reduction of the cross-correlation suggest, for example, that the WBV experimental manipulation may improve the understanding of the mechanisms underlying binocular control.

Vertical direction was of most interest for the study, as it is in this axis that WBV causes more discomfort and more reading errors.[9] WBV between 4 to 8Hz have weighting curves with unity value, demonstrating that these frequencies are the most important ones for human evaluation.[20] A bibliographic review of biodynamics of the human body under WBV showed the importance of the 5Hz frequency on most of the evaluations at the Z-axis.[29]

The amplitude of 0.8m/s² may be considered the mean amplitude for forklift trucks in the vertical direction.[30] As the amplitude increased, the percentage of reading errors also increased.[1] Lewis and Griffin showed a plot of acceleration magnitudes that produced 10% to 30% reading errors for participants subjected to fore-and-aft (X-axis) vibration of a seat with a backrest.[31] For all percentages, at 5Hz, the amplitude for equal reading percentage errors was smaller than the other frequencies. Moreover, at 5Hz, the 0.8m/s² amplitude falls into the 15% percentage error curve, which can be considered a good result in relation to everyday situations.

The current study also analyzed the effect of reading in different types of media (sulfite paper versus tablet) and under different types of lighting (fluorescent versus LED) on eye-movement parameters. Neither the type of media nor the lighting conditions interfered significantly with the eye-movements, both in situations with and without WBV (p>0.05). Although not investigated here, other aspects of the lighting system, such as low-frequency flicker, characteristic of fluorescent lamps, may adversely affect visual performance and reading.[32-34] Aarts et al., for instance, concluded that light is an important factor to minimize the number of errors when reading medication labels.[35] Light-emitting devices are usually short-wavelength enriched, with an unnatural peak at 452 nanometers in the blue light range, activating photosensitive retinal ganglion cells that project to different limbic brain regions, disrupting human physiology.[36-38] The increase of visual exposure to tablet light before bedtime suppresses the sleep-facilitating hormone melatonin, causes phase-delays in circadian rhythm, reduces and delays REM sleep, and reduces alertness the following morning.[36]

Concerning the limitations of the current study, only the volunteer was subjected to the WBV. The text remained stationary even when the volunteer was under vibration, which is more degrading when compared to the simultaneous vibration of the reader and the reading material, or only the vibration of the display.[1] This may be an innovative approach to understand a situation where a forklift truck driver, for example, needs to read something on a shelf. Placing the text on a pedestal outside the vibrating platform eliminated the compensation of the vibration effect by moving the hands. As it is typical to hold a text while being vibrated (e.g., reading while sitting in a car or train), future studies should investigate to what degree it is possible to instantaneously compensate WBV with hand movements to achieve stability of perception. Furthermore, future studies should investigate the exposure to WBV in different directions, frequencies, and amplitudes to better understand its influence on eye-movements during reading and on other visual tasks.

CONCLUSIONS

This work investigated if adults subjected to whole-body vibration, reading in different types of media (paper *versus* tablet) and under different types of lighting (fluorescent *versus* LED), presented a difference in eye-movement parameters during reading tasks. The results demonstrated that whole-body vibration significantly interfered in six out of eight parameters during reading, with a reduction on the number of ocular fixations, and cross-correlation; and increased the reading efficiency, fixation duration, directional attack, and binocular anomalies. These may indicate a difficulty to process the visual information and to synchronously coordinate the binocular movements. Neither the type of media nor the lighting conditions interfered significantly with the eye-movements, both in situations with and without whole-body vibration.

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