Journal of Vestibular Research 23 (2013) 195–201
DOI 10.3233/VES-130500
IOS Press

Dynamic visual acuity (DVA) during locomotion for targets at near and far distances: Effects of aging, walking speed and head-trunk coupling

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Received 11 December 2012
Accepted 20 August 2013

Abstract. This study examined effects of aging, head-trunk coupling (HTcoupling) and walking speed on dynamic visual acuity (DVA) at near and far viewing distances. Ten healthy participants were recruited in 3 groups; young: 20–33 years, Older1: 65–74 years, Older2: 75–85 years. The binocular DVA was measured while walking on a treadmill at 0.75 and 1.5 m/s speeds. The optotype display was placed at 0.5 m for NearDVA and at 3.0 m for FarDVA. On randomly selected trials, HTcoupling was achieved by using a collar. A mix-factor ANOVA (age-group x HTcoupling x speed) was performed separately for the Near and FarDVA. NearDVA declined with HTcoupling ($p = 0.021$). Additionally, NearDVA worsened at the faster speed ($p < 0.001$). At 1.5 m/s speed the differences between Young and Older2 groups were significant ($p = 0.012$) and those between Older1 and Older2 were marginal ($p = 0.085$). FarDVA declined at the faster speed ($p < 0.001$) with no effect of HTcoupling or age-group. NearDVA is more sensitive to normal aging process. These age-related deficits become more apparent at higher walking speeds. Effect of HTcoupling on NearDVA suggests a possible additive effect of insufficient dampening of the vertical movement of the overall head-trunk complex and inability of the linear vestibulo-ocular reflex to compensate for the consequent high discrepancy.

Keywords: Dynamic visual acuity, aging, vestibulo-occular reflex, locomotion

1. Introduction

The ability to maintain visual acuity during activities that impose head movements (e.g. walking or traveling in an automobile) is called dynamic visual acuity (DVA). Assessment of DVA has long been identified as a more practical and powerful measure of functional visual acuity [10]. DVA is primarily subserved by the vestibulo-ocular reflex (VOR) mechanism in which head movement is detected by the vestibular system and the information is then relayed to appropriate cranial nuclei which in-turn send impulses to respective extraocular muscles [30]. Such gaze stabilization achieved through compensatory eye movements is essential for correcting retinal slip and maintaining stability of visual images on the fovea, thus, averting oscillopsia or blurring and preserving visual acu-

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ISSN 0957-4271/13/$27.50

ity during functional activities. Consequently, individuals with vestibular dysfunction, for example, due to pathology [31] or following exposure to microgravity environments as in astronauts [6,27], commonly experience highly debilitating illusory movement or blurring of visual images during daily activities.

Even without pathologies, gradual age-related morphological deterioration is evident in all components of the vestibular system, including receptor hair cells, primary neurons, nerve axons and the vestibular nuclear complex in the brain stem [5,19,25,29]. It is not known if the reported age-related deterioration in the vestibular system components is also associated with gradual degradation of dynamic visual acuity during day-to-day physical activities that induce head movements. This information is important as older individuals are highly dependent on the clarity of the visual information for their overall postural control [2] and blurred vision during dynamic tasks can significantly jeopardize their stability [12].

The proprioceptive input from the neck muscles and neck joint structures can contribute through the cervico-ocular reflex (COR) to improve DVA [22]. Neurophysiological studies have shown that the gain of COR, which is negligible in healthy humans, is significantly upregulated in patients with vestibular deficits [7]. These findings corroborate that information obtained from neck proprioceptive input can provide a compensatory mechanism in case of vestibular deficits. The question is whether this mechanism is also in effect in older individuals for the purpose of compensating for age-related vestibular degeneration. A recent study has reported an upregulation of COR gain in healthy older adults at slow velocities of neck movements [15]. In addition, a psychophysical study has proposed that when compared to young adults, the weighting of neck proprioceptive input increases for the purpose of spatial orientationin older adults [32]. No evidence could be cited that reported COR gain modulations during activities of daily living. In particular, it is not known if the proposed increase in the weighting of the neck proprioceptive information has any implications for maintaining DVA as we age.

Geometrically the required magnitude of compensatory eye movements in the vertical direction in response to head bobbing while walking could be much higher if the target is closer. Paradoxically however, the gain of the otolith-based linear VOR that subserves this compensation is low [17]. In addition to age-related deterioration in otolith function, it is also reported that the ability to attenuate vertical head acceleration while walking deteriorates with increasing age [21]. Therefore, the overall purpose of this study was to examine effects of aging on DVA during walking. The specific objectives were to understand if the distance of the visual target and walking velocity modulate aging effects and to investigate if impeding neck receptor input has a higher impact on DVA in older persons.

2. Methods

2.1. Participants

Healthy participants were recruited in three groups each using a non-probability static group assignment based on their age: 1. Young ($n = 10$, age 20–30 years, 6 women), 2. Older 1 ($n = 10$, age 65–74 years, 5 women) and 3. Older 2 ($n = 10$, age 75–85 years, 5 women). Young subjects were recruited from the university student population and the older participants were recruited from the community. Subjects were included if they did not have history of vestibular and/or neuromuscular pathologies, cervical complaints, dizziness,or greater than one fall within the past year. Since participants were required to walk on a treadmill for repeated trials they were screened for symptomatic lower limb arthritis. Participants with Mini Mental State Examination score $<$ 29/30 were excluded to ensure cognitive health of older persons [11]. Tympanometry screening (GrasonStradlerInc. TympStar, Madison, WI.) [20] was performed bilaterally on all study subjects to verify appropriate middle ear function. All subjects signed an informed consent approved by the University of Kansas Medical Center (KUMC) Human Subjects Committee, Kansas City, Kansas.

2.2. Dynamic visual acuity assessment (DVA)

The DVA instrumentation and software used in this study were developed at the Neuroscience Laboratories, NASA Johnson Space Center, Houston, TX and has been extensively described previously [26]. Briefly, to achieve comparable resolutions the Landolt ‘C’ optotypes were displayed on a Dell laptop computer (Dell, Inc., Round Rock, TX) for DVA assessment at ‘far’ distance (visual target at 3 m) and on micro-display (Liteye Systems, Highlands Ranch, CO) for visual target at ‘near distance’ (0.5 m). The participants were instructed to verbally identify the opening in the ‘C’ optotype that was randomly positioned either up, down, left or right. The optotype size varied between 15 different sizes ranging from 1.0 to −0.4 logMAR. In the logMAR scale 1.0 is equivalent to a 20/200 Snellen ratio, while 0.0 is equivalent to a Snellen ratio of 20/20. Each optotype was displayed for 500 msec in order to be available through a complete step cycle [26].

The optotype display was controlled using a custom-written LabView (National Instruments, Austin, TX) program. Using a psychophysical PEST (Parameter Estimation by Sequential Testing) algorithm, the visual acuity threshold for each condition was estimated as the optotype size in which half of the responses were correct [18]. This point was established using a curve-fitting process based on the correctness of the subject's responses. For all conditions the size of the first optotype was fixed at the middle of the ranges of sizes. The size of each subsequent optotype was determined based on the fit of a logistic function applied to all available responses. By recalculating the curve fit after each presentation and presenting each optotype in the size corresponding to the steepest part of the curve, a higher proportion of the presentations were made nearest to the subject's threshold. The accuracy of the curve improved with each subject response. While the acuity threshold may be established in a clinical setting based on 3 correct responses out of 5 available opotypes at the threshold size, the use of this algorithm could be based on twice as many presentations near the threshold as well as presentations above and below the subject's threshold. Bach [4] determined that this methodology produced stable results with as few as 17 presentations. We used 28 presentations to establish the threshold in all conditions. Participants' responses were entered into the computer by a tester using a numeric keypad. Entering the response on the keypad immediately triggered the next randomly oriented optotype in the series.

Initially, visual acuity was tested in a sitting position for both 'far' and 'near' distances (static visual acuity, SVA). The DVA score was calculated for each testing condition by subtracting corresponding SVA score from the measured acuity in the dynamic condition. This delta score was then reported in a linear logMAR scale. The delta value was used as the DVA outcome measure for all analyses and calculations. Thus, smaller values denoted better performance.

Testing conditions: DVA assessment was performed at walking speeds of 0.75 and 1.5 m/s using a variable speed treadmill (Biodex Medical Systems, Shirley, NY). These walking speeds provided a slow and moderate walking speed.The visual target was placed at 0.5 m and at 3.0 m for 'near' and 'far' conditions, respectively. These distances were chosen based on previous research describing the relationships between viewing distance and generation of eye movements during locomotion [23]. Near distances have been shown to rely more heavily on the linear VOR while far distances rely more on angular VOR [9,33]. To manipulate COR contribution, on randomly selected trial sneck proprioceptive input was precluded by coupling the head to the trunk (HTcoupling, 'fix' condition) using a cervical collar (Procare, Vista, CA used for cervical spine immobilization) [7]. The trials were performed in random order within the blocks of distance condition. Two trials were performed in each condition (total 16 trials). The average time required for a participant to complete the testing was 30 minutes that included rest periods if required and walking on a treadmill for a few seconds to get used to the speed prior to beginning the test.

DVA data collection was carried out at the Landon Center of Aging Human Performance Laboratory, University of Kansas Medical Center. The subjects were allowed to use their normal vision correction during the DVA testing. The subjects first practiced treadmill locomotion until they could walk comfortably at required speeds without using the handrails. All subjects wore a light-weight harness system during the testing on the treadmill to ensure safety. SVA assessment was performed again at the conclusion of the dynamic testing. This post test also served as an internal check to control for fatigue or eye strain that could potentially affect visual acuity measures. Participants' height, body weight and self-selected normal walking speed were recorded for descriptive purposes.

2.3. Statistical analysis

A three-way mixed factor ANOVA with Bonferroni correction was used to test for differences in DVA betweenage-groups and effects of walking speed and HTcoupling [3(age-groups) × 2(HTcoupling) × 2 (speed)] separately for 'near' and 'far' distances since direct comparisons should not be made between these distances due to possible luminance differences at each site. Post hoc analyses were performed to identify pairwise differences between age-groups or if significant interactions were noted. Differences were considered significant at $p < 0.05$ (SPSS Inc., version 19.0).

3. Results

Participant characteristics are displayed in Table 1. The groups were marginally different in their weight.

Table 1
Participant characteristics. A total of 10 participants were recruited in each age-group

variable	Young	Older 1	Older 2	Statistical significance
Age (years)	26.9 (2.9)	67.7 (2.0)	78.8 (2.9)	$F_{(2,27)} = 1030.751$, $P < 0.001$
Height (cm)	169.4 (8.4)	173.5 (12.2)	168.5 (6.6)	$F_{(2,27)} = 0.767$, $P = 0.475$
Weight (kg)	65.5 (12.1)	81.0 (17.8)	67.3 (14.1)	$F_{(2,27)} = 3.277$, $p = 0.054$
Usual walking speed (m/s)	1.33 (0.19)	1.38 (0.15)	1.22 (0.17)	$F_{(2,27)} = 2.218$, $p = 0.128$

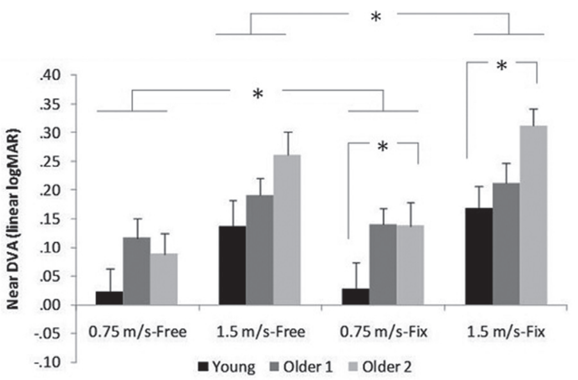

Fig. 1. Mean (SD) NearDVA in the 3 age groups without (Free) and with (Fix) head-trunk coupling. Young: age 20-30 years, Older 1: age 65–74 years and Older 2: age: 75–85 years. Overall, NearDVA was significantly better in Young compared to Older 1 ($p = 0.042$) and Older 2 ($p = 0.027$) groups. NearDVA worsened when the head was coupled to the trunk ('fix' condition) compared to when it was 'free' ($p = 0.021$). The age-groups were not different at 0.75 m/s speed ($p = 0.111$). Conversely, at 1.5 m/s speed the differences between Young and Older 2 groups were significant ($p = 0.012$) and those between Older 1 and Older 2 were marginal ($p = 0.085$).

However, adjusting for height, there were no group differences. There were no significant differences in DVA between the two trials in the same condition. Therefore, the average of the two trials was used as an outcome measure. NearDVA was significantly better in Young compared to Older 1 ($p = 0.042$) and Older 2 ($p = 0.027$) groups. There was a main effect of HTcoupling where NearDVA worsened when the head was coupled to the trunk ('fix' condition) compared to when it was 'free' ($p = 0.021$). NearDVA was also worse at the walking speed 1.5 m/s compared to 0.75 m/s ($p < 0.001$). There was a significant group x speed interaction ($p = 0.034$). Further analysis revealed that the age-groups were not different at 0.75 m/s speed ($p = 0.111$). Conversely, at 1.5 m/s speedthe differences between Young and Older 2 groups were significant ($p = 0.012$) and those between Older 1 and Older 2 were marginal ($p = 0.085$) (Fig. 1).

Age-group or HTcoupling had no effect on FarDVA ($p = 0.479$ and 0.328, respectively). However, Far DVA was significantly better at 0.75 m/s walking speed compared to 1.5 m/s ($p = 0.001$) (Fig. 2).

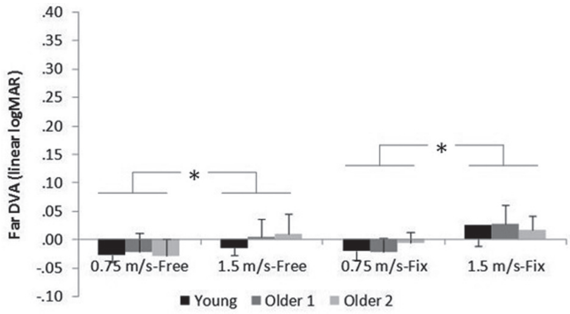

Fig. 2. Mean (SD) FarDVA in the 3 age groups without (Free) and with (Fix) head-trunk coupling. Young: age 20–30 years, Older 1: age 65–74 years and Older 2: age: 75–85 years. Age-group or head--trunk coupling had no effect on FarDVA ($p = 0.479$ and 0.328, respectively). However, Far DVA was significantly better at 0.75 m/s walking speed compared to 1.5 m/s ($p = 0.001$).

4. Discussion

This is the first study that examined effects of aging on DVA during a functionally relevant activity of walking. The aging effect on DVA was more pronounced when the target was at the near distance compared to at the far distance. The effect of head trunk coupling on DVA was found independent of age for NearDVA. However, walking speed had a significant effect on DVA irrespective of the target distance or HTcoupling.

The HTcoupling was performed to prevent head movement independent of trunk movement in order to minimize neck proprioceptive input and therefore, reduce the possibility of evoking COR. The collar used for this purpose is specifically designed to immobilize the neck. Therefore, although kinematic analysis of the head and the trunk was not performed, we expect that it prevented head movements independent of the trunk. The effect of HTcoupling on NearDVA was independent of age and walking speed. It is known that the linear VOR is responsive when the targets are closer, however, the gain of linear VOR is generally lower compared to angular VOR [17]. Additionally, the latency of linear VOR is much higher compared to that of angular VOR [3,8,29]. Therefore, it is possible that linear VOR could be less robust compared angular VOR and a supportive role of COR may be critical when the target is closer to the eyes.

Mulavara and Bloomberg [24] have demonstrated that the vertical translation of the head is reduced when performing a reading task while walking. In addition, head pitch movement further offsets the head bobbing [6] to maximize foveation. The vestibulo colic reflex (VCR) may subserve both these tasks [14]. When a target is closer, the same magnitude of head vertical movement (bobbing) generated during walkingmay necessitate a combination of a larger compensatory head pitch and a further reduction in head vertical movement compared to when the target is farther away. Therefore, it is possible that neck proprioceptive information and the resultant COR play a critical role. When the head is coupled to the trunk, head stabilization independent of the trunk as well as compensatory head pitch movements are precluded and the whole head-trunk complex must be stabilized in the vertical direction. Neuro-mechanically, this could be challenging. The alternative would be large magnitude compensatory eye movements in the vertical direction. However, it is possible that the linear VOR alone is not capable of generating these high magnitude compensatory eye movements even in young healthy adults thus, deteriorating nearDVA. When the target is far the angular VOR is the primary underlying mechanism for maintaining DVA [6]. In addition, the demands on stabilization in the vertical direction are not as high as in NearDVA. It is possible that the angular VOR is capable of generating compensatory eye movements, even when not supported by VCR and COR, independent of age.

Overall, the results demonstrated that there was no age-group related differential effect of HTcoupling on NearDVA possibly suggesting that the contribution of COR to DVA may not increase significantly in healthy older persons while walking at the speeds prescribed in this study. However, Mulavara and Bloomberg [24] have demonstrated that trunk as well as lower limb kinematic strategies contribute to achieve head stabilization in space when performing a reading task while walking. Therefore, future research should examine whether older adults employ compensatory altered/exaggerated lower limb kinematic strategies to stabilize head-trunk complex compared to young adults.

The DVA declined with an increase in walking speed for both near and far targets. Hirasaki et al. [14] have shown significantly higher head accelerations and displacement when walking at higher velocities. It is possible that both linear and angular VOR have limitations for accommodating these high acceleration head movements. Mulavara and Bloomberg [24] measured kinematic responses while walking at approximately 1.7 m/s and did not manipulate walking speed. It is possible that adoption of the kinematic strategies demonstrated by them can be evoked more effectively when walking at a slower speed. However, the effect size of walking speed for NearDVA ($\omega^2 = 0.716$) was twice compared to FarDVA ($\omega^2 = 0.351$) which suggests that the angular VOR is more capable of compensating high magnitude head movements than the linear VOR, to some extent. However, a direct statistical comparison between Near and Far DVA was not performed due to possible luminance differences at the two target locations.

The age-group x speed interaction that was found for NearDVA was not significant for FarDVA suggesting that walking at higher speed did not differentially affect older persons' FarDVA. In contrast, for NearDVA age-group differences became apparent while walking at a faster speed. Overall, this study extracted aging effects on DVA only when the VOR was stressed the most (NearDVA at fast walking speed). These results are in line with a recent study that demonstrated aging effects on DVA using passive head movements in a sitting position [1]. However, lack of aging effect on FarDVA even at faster walking speed may suggest that in healthy older persons a decline in DVA may not be a limiting factor for mobility required in daily activities. However, these results should be interpreted carefully as first, it is not clear if older persons, in fact, adopt different or exaggerated compensatory lower limb kinematic strategies that sufficiently supplement the angular VOR when the target is far and second, the maximum speed used in this study was 1.5 m/s. It is possible that even FarDVA may demonstrate aging effect while moving at speeds > 1.5 m/s.

The first limitation of this study is the inability to decipher the possible supportive role of the smooth pursuit eye movement [13] particularly with respect to the more stable double support phase of the gait cycle. It is possible that the older persons used smaller step length and higher cadence as compared to the young adults, thus relatively increasing their double support phase and thus, minimizing the age effect in FarDVA. It is also possible that, relatively speaking, the supportive role of the smooth pursuit eye movement was higher at slower walking speed compared to fast walking speed thereby resulting in main effect of speed in FarDVA. Since the smooth pursuit eye movement is known to be less accurate in vertical direction (as compared to horizontal direction), it is possible that when large compensations were required in the vertical direction in NearDVA, the age-related differences became apparent. Second, it is possible that similar to active head movements [16] the central nervous system has learned to generate anticipatory vertical eye movements in addition to head pitch movement to supplement the less robust linear VOR within the scope of a well-learned task of normal walking thus, demonstrating the effect of HT coupling. However, the linear VOR is not capable of overcompensation required due to HTcoupling thus, demonstrating the main effect of HTcoupling on NearDVA. The direct evidence for anticipatory vertical eye movements during walking could not be cited in humans. However, anticipatory eye movements have been observed in animals with bilateral labyrinthectomy and when neck proprioceptive input is not available suggesting the role of the efference copy [16]. However, majority of the evidence is for voluntary head movements. The head movements during walking are not voluntary. In this regard anticipatory eye movements could be compared to well-learned anticipatory postural responses. The second limitation is the inability to exactly pinpoint the structural causality of the age-related differences observed for NearDVA. It is possible that age-related changes in ocular muscle may contribute to these differences.

5. Conclusion

NearDVA that puts significant demands on otolith-based gaze stabilization is more sensitive to normal aging process and age-related deficits become more apparent at higher walking speeds. Closer targets require significantly higher gaze compensation in the vertical direction. Effect of the collar on NearDVA suggests a possible additive effect of insufficient dampening of the vertical movement (bobbing) of the overall head-trunk coupled complex and inability of the linear VOR to compensate for the consequent high discrepancy, during walking. Lack of collar and age effect on FarDVA suggests sufficient stabilization of the overall head-trunk complex within the required magnitude and minimum age-related decline in angular VOR, respectively, for this purpose

Acknowledgement

This work was supported by the School of Allied Health Research Grant, University of Kansas Medical Center, Kansas City, Kansas to Dr. Nandini Deshpande,

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