Evidence for the use of rotational optic flow cues for locomotor steering in healthy older adults

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Submitted 29 March 2011; accepted in final form 1 June 2011

Berard JR, Fung J, Lamontagne A. Evidence for the use of rotational optic flow cues for locomotor steering in healthy older adults. J Neurophysiol 106: 1089–1096, 2011. First published June 8, 2011; doi:10.1152/jn.00277.2011.—Optic flow is a powerful visual cue for the control of locomotion. Considerable research has focused on how healthy young people use and perceive optic flow. However, little is known on how older adults use this type of visual motion to control walking. The purpose of this study is to investigate the ability of young and older adults to adjust their physical walking trajectory in response to a rotation of the optic flow presented in a virtual environment. Ten healthy young adults (mean age 23.49 ± 4.72 yr) and 10 healthy older adults (mean age 76.22 ± 3.11 yr) participated in the study. Subjects were instructed to walk straight in a virtual environment viewed within a head-mounted display unit as they walked overground for 5 m, while the focus of expansion was gradually rotated to the left or the right by 40°. All subjects responded with a similar strategy by rotating their head and body in the direction away from the orientation of the perturbation. The younger subjects achieved almost complete corrections and had very small net heading errors. In contrast, the older adults had delayed and smaller reorientations, particularly in the head, thus showing significantly larger heading errors compared with younger subjects. We conclude that older adults retain the ability to use optic flow to control their walking trajectory, although smaller, delayed head rotations and larger heading errors may indicate an age-dependent effect on sensorimotor coordination.

Visual perception has been examined in older adults who show more susceptibility to noise in the perception of global flows, and the onset of age-related deficits appears suddenly in those over 70 yr of age, rather than gradually over time during the aging process (Bennett et al. 2007). Interestingly, not only are there deficits in motion perception, but older adults have poorer judgments in the identification of the direction of motion, even in the cases where global motion are correctly detected (Ball et al. 1983; Bennett et al. 2007). In terms of radial flow perception, the findings are mixed. Some have shown that older adults had higher motion detection thresholds than their younger counterparts in viewing shifting FOEs during sitting (Warren et al. 1989). Others have reported that the thresholds for radial motion detection were not significantly different between young and old subjects (Atchley and Andersen 1998; Billino et al. 2008). Also, it has long been known that older adults have impaired visual processing speeds, requiring more time to complete visual tasks (Kline and Birren 1998; Billino et al. 2008). Furthermore, visual processing deficits have been linked to real-world risks, such as an increased risk of falls (Owsley and McGwin 2004) or car crashes (Owsley et al. 1998). Despite what appears to be in some aspects a diminishing capacity for visual motion perception with advancing age, older adults tend to become more reliant on visual cues for postural control and have greater challenges with multisensory integration (Bugnariu and Fung 2007; Jeka et al. 2010; Lord 2006; Lord and Webster 1990). What this paradox means for locomotor control is unclear.

Older adults have been shown to be able to modulate their gait parameters in response to changing optic flow speeds (Chou et al. 2009; Lamontagne et al. 2007), suggesting that they process speed information in a similar manner to younger adults. However, their ability to use optic flow cues for heading may not be as robust as in healthy young subjects. We have previously (Berard et al. 2009) examined the ability of older adults to adjust their walking trajectory in response to translational optic flows expanding from different FOE. Despite being explicitly instructed to adjust their locomotor strategy, the older adults in this study showed very little response. This inability of the older adults to adjust their gait may be related

FUNCTIONAL LOCOMOTION is tightly regulated by the senses. Vision is arguably the most dominant sensory cue to guide us as we navigate through the environment. Particularly, optic flow or the perception of self-motion provides important information on heading direction (Gibson 1950). When one is walking straight ahead, the flows presented at the retina have a radial pattern originating from a central point, known as focus of expansion (FOE). During simple, straight-ahead walking, the FOE indicates heading direction, arising from forward translation (Gibson 1950). However, this straightforward example perhaps oversimplifies the role of optic flow in daily life. Under most circumstances, the eyes and head are free to rotate, which adds a rotational component to the translation flow pattern already present at the retina. To determine heading accurately, the central nervous system (CNS) must accurately decompose the rotational component from the translational flows. It would appear that when optic flow is readily available, healthy young individuals are quite successful in determining heading direction from flow patterns alone (Li et al. 2006; Warren and Hannon 1988; Warren and Rushton 2009). Considering the visuomotor changes associated with aging, it is important to examine the ability of older adults to use optic flow while walking, but most research has focused on the psychophysics of optic flow perception and its role in navigation and steering in healthy young subjects.
to the type of flow presented. Recently, we showed that subjects behaved differently in response to different types of optic flows with the same level of textual cues (Sarre et al. 2008). When healthy young subjects were presented with flows where the FOE was shifted laterally in a translational manner during walking, subjects showed large mediolateral deviations in their walking trajectory and very little segment (e.g., head, trunk, or pelvis) reorientation. However, when the FOE was rotated (such as what is experienced during an eye or head turn), as opposed to being translated, subjects showed smaller center of mass deviations and stronger segmental reorientations in the opposite direction to the flow rotation. The fact that older adults did not respond to translational cues does not necessarily imply that they have difficulty responding to flows with a rotational component. When one is walking straight ahead and performing an eye and/or head turn, the resulting retinal flow is a radial flow with a rotation of the FOE, much like the stimulus presented in the study of Sarre et al. (2008). This condition has high ecological validity and little ambiguity for detection or interpretation. Given the high frequency of occurrence and importance of this type of visual information, we hypothesized that healthy older adults can properly interpret rotational cues for locomotor heading. The purpose of this study was to investigate the effects of aging on the ability to use rotational optic flow cues to control walking trajectories in a virtual environment. We expected older adults to be employing similar visuomotor control strategies to younger subjects if they are able to adjust locomotor steering with rotational optic flow changes.

METHODS

Subjects. Ten healthy young subjects (mean age 23.49 ± 4.72 yr) and 10 healthy older adults (mean age 76.22 ± 3.11 yr) participated in the study. All participants in the study were naive to the experiment and had no prior experience moving in virtual environments. Subjects had corrected-to-normal vision, scoring at least 20/40 on a standard eye exam (with eyeglasses if required) and had no self-reported history of eye disease, including cataracts, macular degeneration, or glaucoma. None of the participants had any self-reported musculoskeletal or neurological conditions interfering with locomotion. They were also screened with the Dizziness Handicap Inventory (score of 24 or 25 out of 25 indicating absence). As well, subjects were free of major cognitive deficits, as reflected by scores of 27 or higher on the Mini Mental Status Exam. All subjects signed an informed consent form that had been approved previously by the institutional ethics board.

Experimental set up. Subjects walked overground in a large open space in the laboratory (12 × 8-m walking area) while wearing a stereoscopic helmet-mounted display unit (HMD; NVisor with 60° diagonal field of view and 1,280 × 1,084-pixel resolution). The scene presented in the HMD was of a room with the same virtual dimensions as the experimental walking area in the laboratory (Fig. 1A). Subjects were outfitted with 39 passive reflective markers on anatomical landmarks as defined in the Vicon Plug-in Gait model. Kinematics data of the head and whole body were captured at 120 Hz with a 12-camera Vicon-512 system. Movements of the head were tracked in real time via three markers placed on the HMD and were used by the CAREN-3 (Computer Assisted Rehabilitation Environments, MOTEK) to update the subjects’ perceived position and orientation in the virtual scene. This allowed for movements of the head to be synchronized and displayed in the HMD in real time, with a negligible delay of 25 ms.

Protocol. Subjects were instructed to “walk straight in the virtual world,” i.e., their task was to walk straight with respect to the scene that was displayed in the HMD. In perturbation conditions, once the subject walked 1.5 m, the scene would gradually rotate to the right or the left so that the total rotation was 40° to the left or right over 3.5 m of forward walking (at an average angular velocity of 11.4°/m). The actual rate of perturbation was a function of the walking velocity of the participant. The subjects were also exposed to control trials without any perturbation in the virtual scene. The order of trials was randomly presented. Subjects performed 6 trials in each direction for a total of 18 trials. Before data collection began, subjects were given three to five trials that were not recorded to allow them to familiarize themselves with the task. All subjects indicated that they were comfortable in the virtual environment and appeared to walk normally.

Data analysis. Joint angles and the body’s center of mass (CoM) trajectory were calculated in three dimensions with the Vicon Plug-in Gait model using marker positions and anthropometric measurements.

Fig. 1. A: image of the scene viewed by participants. The change in position of the focus of expansion (FOE) indicates the final position of the FOE after it has been rotated in the perturbation conditions. B: schematic of the optic flow experienced by participants from the rotated FOE. C: diagram of predicted behavior. As the FOE is rotated to the left, the subjects perceive themselves as going leftward and rotate their physical walking direction angle (heading) and head angle in the rightward direction to keep straight in the virtual environment. The variable net heading correction is the sum of the heading angle (θ1) and head angle (θ2), and reflects the total correction in the virtual environment.
RESULTS

Subjects responded to a rotational optic flow by steering in an opposite direction, as shown by the representative traces of heading and body orientation data in Fig. 2 for two participants, one young and one old. In response to a 40° leftward FOE rotation condition while walking forward, both participants veered toward the right, opposite to the direction of perturbation. Although both the young and the old participants adopted a similar orientation strategy, it is evident that the younger subjects had a greater magnitude of response, most notably in head and trunk reorientation.

Outcome variables. Segmental angles in the yaw direction were calculated for the head, trunk, pelvis, and feet throughout the trial. In addition, heading orientation was calculated by determining the instantaneous angular deviation of the CoM trajectory in the horizontal plane, as from the onset of optic flow perturbation. Because the scene viewed by participants could be adjusted by either rotating the head or changing the angle of displacement from the CoM origin point, combining head yaw and heading most accurately reflects the camera view of the scene in the HMD. Therefore, steering performance was assessed using a “net heading correction” variable based on the sum of head yaw and heading. Steering performance was also quantified by dividing the amount of net correction by the magnitude of perturbation and is expressed as a percentage. The heading error was calculated as the difference between 100% and the net correction. Net heading corrections and percent heading errors were calculated throughout the trial; however, for ease of statistical analysis, data were retained for analysis at specific points along the trajectory corresponding to optic flow perturbations of 10°, 20°, 30°, and 40°. Onset of net correction was also calculated by measuring the point at which it deviated by 2 standard deviations from average position in the 1.5 m preceding perturbation.

To obtain an overall indication of how participants performed throughout the trial, we calculated the root mean square (RMS) between the theoretically perfect response (the inverse of the perturbation) and the net heading correction. Because RMS is sensitive to trial length, we resampled the data so that each trial length was equal in size, and the computed variables are expressed as a function of perturbation.

Finally, to provide insight into the variability of our subjects, and to determine how consistent subjects were in their responses, we calculated the mean coefficient of variation of the net correction (CV) of responses for each participant.

Statistical analysis. For each outcome variable, the six trials in each condition were averaged in each subject. Segment yaws of the head, trunk, pelvis, and feet at the end of the trial were examined using a multivariate analysis of variation (MANOVA), with one between-subject factor (age group: young vs. old) and one within-subject factor (FOE rotation: right vs. left vs. neutral). A mixed two-way analysis of variance (ANOVA) was performed for heading orientation, heading correction, and percent heading error. The between-subject factor was age group (young vs. old), whereas the within-subject factor was FOE rotation (right vs. left vs. neutral) for heading orientation or perturbation intervals (10°, 20°, 30°, and 40°) for heading correction and percent heading error. Student’s t-tests were performed to compare RMS and CV scores between young and old subjects.

Where significant main or interaction effects existed, Tukey’s post hoc comparisons were used to identify differences between groups. The level of significance was set at $P < 0.05$. Statistical analysis was performed using PASW 18.

Walking velocity and flow rate. There was no significant difference in walking speed between the younger and older adults ($0.928 \pm 0.152$ vs. $0.884 \pm 0.132$ m/s, respectively; $P = 0.341$). Since the optic flow was delivered as a function of the subject’s walking speed, there was also no significant difference between the two age groups ($P = 0.282$) in the flow rates presented ($10.35 \pm 1.86\%$ in young vs. $9.77 \pm 1.43\%$ in old).

Segment yaw and heading. All the participants responded to the visual stimulus by rotating their bodies in a direction opposite to the FOE rotation. Figure 3 shows the segmental yaw of the head, trunk, pelvis, and feet at the end of the trial, that is, when reaching 40° of visual rotation. There was a significant main effect due to FOE rotation in all the segment orientations [head: $F(2, 59) = 374.05, P = 0.000$; trunk: $F(2, 59) = 211.479, P = 0.000$; pelvis: $F(2, 59) = 87.147, P =...
There was a significant main effect due to FOE rotation on heading \( [F(3, 72) = 68.576, P = 0.000; \text{Fig. 4}] \). Post hoc analysis indicates that the heading changes seen in each of the FOE rotation changed significantly from the neutral FOE condition. The young subjects trended toward having larger heading values; however, this failed to reach significance \( [F(1, 72) = 2.773, P = 0.100; \text{Fig. 4}] \).

To ascertain whether there was an overall asymmetry in response due to the rotational perturbation (left or right), we compared the responses for head yaw, heading, and net heading. There were no significant differences found \( (P = 0.324, P = 0.460, \text{and } P = 0.179, \text{respectively}) \). As such, the values for the left and right sides were adjusted in polarity to account for directional differences and collapsed together for the remainder of the analysis.

Performance measures. There was a main effect due to age in terms of the percent heading error \( [F(1, 18) = 58.9, P = 0.00; \text{Fig. 5}] \). Closer examination of the magnitude of errors revealed that, at various intervals (20°, 30°, and 40°), the young subjects had significantly fewer errors in performance compared with the older adults \( [F(1, 18) = 17.410, P = 0.001; \text{Fig. 5}] \).

Figure 6 illustrates typical net heading responses from a young subject and an old subject who are representative of their groups. The younger subjects overall showed better performance than the older subjects. We measured the net heading correction for each participant at 10°, 20°, 30°, and 40° intervals of perturbation (Fig. 7A). Both young and old participants adjusted their locomotor trajectory in response to flows; however, the net heading correction was greater in the young adults throughout the trial \( [F(1, 18) = 17.410, P = 0.001] \). Because there was no statistical difference in heading between the groups, the difference in net heading correction was a result of the younger adults having more head rotation than the older subjects (see Figs. 3 and 4). When we expressed net correction in terms of its components, we found that not only did the older adults have less absolute head rotation, but they also tended to have smaller relative head reorientation with respect to net correction; however, this difference in magnitude was only significance at 40° [i.e., at the end of the walking trial; \( F(1, 18) = 9.03, P = 0.007; \text{Fig. 7B} \)]. Furthermore, analysis of the timing of net heading correction adjustments revealed a significant delay in older subjects \( [F(1, 18) = 6.95, P = 0.018] \) in that they began reorientation only after 8.74 ± 3.85° of rotational FOE perturbation, whereas younger subjects started reorienting as early as 5.07 ± 1.60° of rotational FOE perturbation.

The RMS yields an overall measure of the variability in performance throughout the trial, as opposed to simply sampling at discrete points. When we compared the groups, we found that younger adults had a significantly smaller score (6.86 ± 1.35°) than the older adults \( [12.27 ± 4.47; F(1, 18) = 12.090, P = 0.003] \). In terms of the coefficient of variation, we also found that older adults had significantly more variability in their responses \( [32.57 ± 5.84% \text{ in young vs. } 59.94 ± 28.29% \text{ in old}; F(1, 18) = 8.896, P = 0.008] \).

Fig. 3. Comparison of average and SD of segmental yaw angle changes at the end of the walking trials across perturbation conditions and between the age groups.

0.000; right foot: \( F(2, 59) = 56.203, P = 0.000 \); left foot: \( F(2, 59) = 109.475, P = 0.000 \). There was also a significant interaction due to age and FOE rotations for all segment orientations aside from the right foot [head: \( F(2, 59) = 24.769, P = 0.000 \); trunk: \( F(2, 59) = 8.259, P = 0.001 \); pelvis: \( F(2, 59) = 5.094, P = 0.009 \); right foot: \( F(2, 59) = 0.440, P = 0.569 \); left foot: \( F(2, 59) = 6.792, P = 0.02 \)]. Although all subjects responded to the flows presented, the young subjects generally responded with greater magnitude of all segment rotations than the older subjects.

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DISCUSSION
Although older adults are known to be more visually dependent in the control of balance and posture (Bugnariu and Fung 2007; Sundermier et al. 1996), little is known on whether or how visual cues can guide locomotion in the elderly. This study provided evidence that older subjects can indeed use optic flow to guide locomotion, because they were able to reorient their posture (head and or body) in the direction opposite to the FOE rotation, thus correcting their walking path in the virtual environment. We found clear segment reorientation responses for both the older and younger adults, albeit smaller and delayed in the older subjects. This finding contrasted with previous research using translational flow perturbations (Berard et al. 2009) that showed little or no change in walking trajectories in older adults, resulting in large heading errors in the virtual environment. We attribute this marked difference to the differences in the flows presented. Optic flows were perturbed by rotational FOE changes in the present study, whereas a linear mediolateral translation of the FOE was used in the previous study. Previous work has also shown that healthy young subjects showed markedly different steering strategies based on the flow type presented (Sarre et al. 2008). Our findings clearly indicate that aging effects on visuomotor control are specific to the types of flow presented. It might be that patterns of visual motion with high ecological validity are more resilient to aging effects. We presented a flow pattern that mimics walking with an eye or head turn, which is equivalent to a radial flow with a rotation of the FOE. Such stimuli are regularly encountered in daily living and are important for heading and navigation. The ability to interpret this type of flow seems to be less dependent on age. Mediolateral translational flow patterns, however, are rather peculiar and not regularly encountered in the natural environment. There is less ecological benefit to maintaining the ability to respond to these types of visual cues, resulting in more prominent age-dependent changes.

The literature does suggest that at the psychophysical level, the effects of aging on visual motion perception are not general, but rather are specific to the type of visual motions presented. Older adults are worse at detecting lamellar or translational flow cues (Billino et al. 2008; Snowden and Kavanagh 2006; Trick and Silverman 1991). In contrast, the perception of radial flow cues (similar to what was presented in this study) is not affected by aging (Atchley and Andersen 1998; Billino et al. 2008).

In this study we focused on the role of optic flow in steering control; however, optic flow is involved in the regulation of walking speed (Pailhous et al. 1990). Others have shown that older adults respond to flow speed and asymmetries in a similar manner to younger adults (Chou et al. 2009). Taking these findings together, we conclude that healthy older adults retain their ability to use optic flow cues for spatial navigation and steering.

Altered visuomotor control. Given that the older adults in our study did respond to the changing flows, it is clear that they were able to perceive the flows presented, and they employed a similar reorientation response strategy to younger subjects. Despite these similarities, the older adults here had systematically smaller and delayed segmental reorientations, particularly that of the head, and they had larger correction errors throughout the trial, which reveals some age-dependent changes. These differences may result from impairments in lower level visual motion processing systems. It is well documented that older adults compared with younger subjects have...
slower processing times for visual motion and worse performance in the discrimination of speed (Norman et al. 2003; Raghuram et al. 2005; Snowden and Kavanagh 2006) and direction (Bennett et al. 2007). Snowden and Kavanagh (2006) measured motion coherence thresholds through a range of speeds. They showed that there was an effect due to age, with older adults having significantly worse scores than their younger counterparts; however, this effect was only present at slow speeds (<4°/s). This is somewhat contrary to what was presented by Wojciechowski et al. (1995), who found age-dependent differences at display speeds of 28°/s. The interaction between speed of visual stimulus and aging is unclear. In fact, the speed of displacement may not even be the most important metric to consider. Some have argued that stimulus displacement per frame of movement may be a better indicator for spatial integration (Snowden and Braddick 1991; Snowden and Kavanagh 2006). Our data show that the onset of steering response was later for the older adults than the younger subjects. Young adults responded after 5° of perturbation, whereas the older adults did not begin correcting until after 9° of visual perturbation. This lag in response does suggest altered visual motion processing, although the possibility of delayed motor responses cannot be ruled out. Furthermore, such a process requires transforming visual information into motor actions that are appropriately scaled and timed (Paquette and Fung 2011).

Raghuram et al. (2005) showed that older adults improved their speed discrimination when given longer response times (500 vs. 1,000 ms). Others have also shown that older adults improve direction identification with longer stimulus expo-

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Fig. 6. Net corrections of a sample trial from 1 young (A) and 1 older adult (B). The shaded line shows the inverse of the perturbation, which would be the perfect (ideal) response to the perturbation. The solid line reflects the net correction achieved by rotations of the head and heading direction.

Fig. 7. A: comparison of net corrections at different intervals of FOE changes during walking between subject groups. The solid components represent the amount of corrections from heading, and the patterned sections reflect the corrections achieved from head turning. B: net correction expressed as the relative contribution of head turn and heading with respect to the total correction at different intervals of FOE changes during walking.
sures (Bennett et al. 2007), suggesting that older adults take more time to process visual motion. Nonetheless, neither of these studies showed that increased viewing time improved the performance of the older adults to the level of younger adults, even if the longer exposure clearly improved temporal integration in the older adults. In the present paradigm, subjects also had to respond in real time as they walked through the virtual environment, and with every step forward the perturbation increased. As such, the perturbation was constantly changing, and a good performance involves predicting the perturbation with each step. The higher RMS values show that the older adults in this study consistently deviated from “perfect performance” compared with the younger subjects.

We also found that the older adults had much more variability in their strategies compared with the younger adults, as reflected by the higher CV score. This measure reveals performance differences between trials of the same condition. The younger adults typically respond in much the same way each time a particular condition is presented. There is little or no practice effect with the randomized presentation of optic flow changes. However, optic flow can drive the recalibration of the visuomotor system (Bruggeman et al. 2007), and for the young this may be happening over the course of a single trial. For older adults, visuomotor recalibration occurs much more slowly (Jeka et al. 2010), which could account for the higher variability of responses in older subjects.

Age-dependent changes in locomotor steering. Older adults employed the same basic strategy as the younger subjects, with small mediolateral deviations of the CoM and the majority of the correction coming from a head turn. Similarly, others have reported that older adults employ similar steering strategies as younger subjects when performing a preplanned turn (Akram et al. 2010; Fuller et al. 2007). But what is a striking difference between the groups in our study is that the older adults consistently had smaller head rotations. The young and old did not differ significantly on their heading changes, but the older adults showed approximately only one-half the head-turn magnitude that the young adults showed. The smaller responses are not related to neck mobility issues, because no subjects had restricted range of head or neck movements when measured during sitting.

We believe that the smaller head rotations may arise from a conflict of sensory perception. In this study, when the rotational perturbation is applied, the information at the retina can increase. As such, the perturbation was constantly changing, and a good performance involves predicting the perturbation with each step. The higher RMS values show that the older adults in this study consistently deviated from “perfect performance” compared with the younger subjects.

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We believe that the smaller head rotations may arise from a conflict of sensory perception. In this study, when the rotational perturbation is applied, the information at the retina can be interpreted by the CNS as a head or eye turn (or that one is walking along a curved path). However, the information from the vestibular and proprioceptive systems would suggest otherwise. To resolve this conflict, the older adults might adopt a more “en bloc” strategy to facilitate the interpretation of the conflicting sources of sensory feedback, since head stabilization in space has been observed to be a priority in situations of sensory conflict (Bugnariu and Fung 2007, 2010).

Limitations. One of the limits of this work is that we did not do thorough psychophysical testing of our subjects and their ability to perceive different visual patterns. Without this information, it remains unclear whether performance differences are related to perception or the ability to use perceptual information (action). Fortunately there has been an abundant amount of work assessing changes in the aging visual system (as reviewed by Owseley 2010) to draw on in the interpretation of present findings. The caveat to this is that most work to date has focused on perceptual evidence, which may or may not be meaningful for the repertoire of motor performance in a more ecological context, such as during walking.

Conclusion. This study provides new insights on the effects due to old age on optic flow-mediated locomotor responses. It is clear that when examining aging effects, one must consider the context in which the study was performed. The rotational FOE perturbation used in this study elicited similar heading and postural orientation responses that are less age dependent compared with responses elicited by translational FOE perturbations used previously, although the age-dependent effects on the magnitude and latency of segmental reorientations are still apparent. Unlike translational flows, rotational optic flows are commonly experienced in daily life, and the ability to interpret rotations of the FOE seems preserved in older adults.

References

ACKNOWLEDGMENTS

No conflicts of interest, financial or otherwise, are declared by the authors.

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