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Normal aging increases postural preparation errors: Evidence from a two-choice response task with balance constraints

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ABSTRACT

Correlational studies indicate an association between age-related decline in balance and cognitive control, but these functions are rarely addressed within a single task. In this study, we investigate adult age differences in a two-choice response task with balance constraints under three levels of response conflict. Sixteen healthy young (20–30 years) and 16 healthy older adult participants (59–74 years) were cued symbolically (letter L vs. R) to lift either the left or the right foot from the floor in a standing position. Response conflict was manipulated by task-irrelevant visual stimuli showing congruent, incongruent, or no foot lift movement. Preparatory weight shifts (PWS) and foot lift movements were recorded using force plates and optical motion capture. Older adults showed longer response times (foot lift) and more PWS errors than younger adults. Incongruent distractors interfered with performance (greater response time and PWS errors), but this compatibility effect did not reliably differ between age groups. Response time effects of age and compatibility were strongly reduced or absent in trials without PWS errors, and for the onset of the first (erroneous) PWS in trials with preparation error. In addition, in older adults only, compatibility effects in the foot lift task correlated significantly with compatibility effects in the Flanker task. The present results strongly suggest that adult age differences in response latencies in a task with balance constraints are related to age-associated increases in postural preparation errors rather than being an epiphenomenon of general slowing.

1. Introduction

Adult human aging often is associated with decline in balance and postural control [1–4] as well as reductions in cognitive control, especially in tasks with increased complexity [5], or requiring inhibition of prepotent responses [6]. Correlational and dual-task studies provide evidence that links between sensorimotor performance and cognitive function increase with advancing adult age [3,7]. Moreover, deficits in executive control in older adults have been related to balance problems, cognitive-balance interference, as well as fall risk [8–11]. In this study, these functional domains are integrated in a choice-response task with balance constraints and different levels of stimulus-response compatibility, to assess the interaction between age-related deficits in balance and cognitive control within a single task.

Lifting one foot from the floor or starting to walk from a standing position is an apparently simple, everyday motor act, which however requires integrating the focal movement of lifting a foot with balance requirements for maintaining an upright posture [12]. As lifting one foot from the floor changes the base of support, it is usually preceded by a preparatory weight shift (PWS) consisting of a weight transfer to the opposite limb. This weight shift can be detected as a transient *increase* of the ground reaction force (GRF) of the to-be-lifted leg, accelerating the body to the opposite side. Older adults have been found to show increased step latencies and postural preparation errors (PWS inconsistent with the required response) during gait initiation and directional stepping, especially when participants could not preselect the stepping leg [13,14]. Combining a lateral stepping task with a stimulus-response compatibility paradigm, Sparto, and collaborators found increased PWS errors for incongruent compared to congruent stimulus-response conditions, and this compatibility effect was more pronounced in older adults [15].

We recently introduced a whole-body response paradigm manipulating response conflict in terms of automatic imitation tendencies [16]. Participants in an upright bipedal standing

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position were cued symbolically (letter L vs. R) to lift the left or right foot from the floor. Response conflict was manipulated by visual distractors showing congruent, incongruent or no foot lift movement (as a baseline condition). Response times and number of PWS errors were increased in the incongruent condition compared to the congruent condition.

The aim of this study was to assess whether and how these results from a stimulus-response compatibility paradigm with balance constraints [16] generalize to older adults. The study thereby also tests the generalizability of results found in gait initiation or stepping paradigms [13,15] to a simpler foot lift movement. Specifically, we assess to what extent (1) older adults show degraded task performance compared to young adults (in terms of response latencies and PWS errors), (2) compatibility effects differ between young and older adults, (3) response latency differences between age groups and between conditions are related to PWS errors, and (4) inter-individual differences in compatibility effects are related across tasks.

2. Methods

2.1. Participants

Sixteen healthy young and 16 healthy older adults (eight women per group) participated after providing written informed consent. All participants were right-handed and reported no medical history of neurological or balance-related conditions or chronic pain. Older participants were screened for dementia [17]. Detailed participant information can be found in Table 1. Experimental data from the young adults have been published in a previous study [16].

Participants received a compensation of 10 Euro per hour. This study was approved by the Ethics Committee of the Max Planck Institute for Human Development.

2.2. Setup and data acquisition

Ground reaction forces (GRF) were measured separately for each foot by two force plates (9286AA, Kistler Instruments, Wintertur, Switzerland). Foot positions were marked by two pieces of carpet (30 cm by 12 cm), placed at a lateral distance of 10 cm and an angle of 10°. Visual stimuli were back-projected to a screen placed 150 cm in front of participants. The size of the visual stimuli on the screen was 72 × 54 cm (symbol cue: 7 × 8 cm), presented 40 cm above the floor.

Kinematic data were recorded using an optical motion capture system (Vicon, Oxford, UK) with four reflective markers at relevant landmarks (toes, sacrum, C7). Kinematic and force plate data were recorded synchronously at sampling rates of 100 Hz and 1000 Hz, respectively.

2.3. Task and procedure

For the main experimental task, participants stood with each foot on one of the force plates in the designated areas, facing the projection screen. They were instructed to lift one foot from the floor as quickly as possible (to a height about mid-way between ankle and knee of the other leg) in response to a *symbolic* or *movie cue* (described below). Based on pilot experiments, the beginning of each trial was initiated automatically when the GRF asymmetry between left and right foot remained below 20% of the participant's body weight (BW) for at least 300 ms.

Between trials, the lower legs of a person were displayed on the projection screen (Fig. 1, top panel). Cue presentation started after a pseudorandom delay (500–900 ms). In the *symbol cue* condition, the letter L or R was shown between the feet for 566 ms, the task being to lift the corresponding (left or right) foot. In the *movie cue* condition, an animated sequence showing a foot lift was presented (two intermediate images for 33 ms, final image for 500 ms), and the task was to lift the foot on the same side as the model on the screen. Presentation duration of the intermediate images (33 ms) was doubled relative to a previous study on finger movements [18] in line with the greater complexity and duration of the foot lift movement. Stimuli from both cueing conditions were presented separately (baseline condition, i.e. symbolic cue without movement distractor, or vice versa) or in a congruent (Fig. 1, bottom left) or incongruent (Fig. 2, bottom right) combination.

The *symbol cue* (A) and *movie cue* (B) conditions were presented in four blocks in an ABBA or BAAB sequence, counter-balanced across participants. Each block consisted of 60 trials (20 baseline/congruent/incongruent) in pseudo-random order, resulting in 240 experimental trials per participant. Twelve practice trials were provided before the first and second block (first occurrence of each Cue Type condition). Experimental programming was done in Matlab R2011b (MathWorks) using the PsychToolbox [19,20].

Additional measures of balance and cognitive control were assessed prior to the main task/experiment: Balance performance was independently assessed as one-leg standing time (up to 30 s, best of two trials), for both legs and both with open and closed eyes. Inhibition of incompatible distractor information was assessed in a standard (manual) Flanker task [21], with accuracy and response time in correct response trials as dependent measures.

2.4. Data analysis

Custom-written Matlab routines were used to analyze force plate and kinematic data, as described below. Trials were excluded (2.9% of all trials) if the force asymmetry at cue onset exceeded 20% BW, if the foot lift occurred earlier than 200 ms or later than 2000 ms after cue onset, or if the wrong foot was lifted.

Table 1
Participant characteristics (age, weight, height, physical activity), performance (MMSE, one-leg standing), and interference effects (foot lift and Flanker). Values are indicated as group means (SD). Statistical tests for age differences (two-sample t-tests) are reported where appropriate.

Test/measure	Young adults	Older adults	Age effect
Age (years)	25.4 (3.2)	67.4 (4.7)	
Weight (kg)	70.9 (10.9)	74.8 (9.1)	$t(30) = 1.12$, $p = 0.27$
Height (cm)	177.3 (12.0)	171.9 (12.5)	$t(30) = -2.0$, $p = 0.055$
MMSE [17]	–	28.4 (1.3)	
Physical activity [33]	8.25 (1.61)	9.06 (0.84)	$t(30) = 1.19$, $p = 0.09$
One-leg standing, eyes open (s)	29.9 (0.25)	24.7 (6.3)	$t(30) = -3.27$, $p = 0.003$
One-leg standing, eyes closed (s)	22.7 (8.2)	4.4 (2.7)	$t(30) = -8.54$, $p < 0.001$
Foot lift time interference, incongruent–congruent (ms)	75.4 (41.3)	103.3 (59.4)	$t(30) = 1.54$, $p = 0.13$
PWS error interference, incongruent-congruent (%)	33.8 (20.4)	35.3 (19.1)	$t(30) = 0.22$, $p = 0.83$
Flanker RT interference, incongruent–congruent (ms)	80.3 (29.7)	95.7 (46.5)	$t(29) = 1.09$, $p = 0.28$
Flanker accuracy interference, incongruent–congruent (%)	−3.0 (2.9)	−11.7 (6.4)	$t(29) = -4.84$, $p < 0.001$

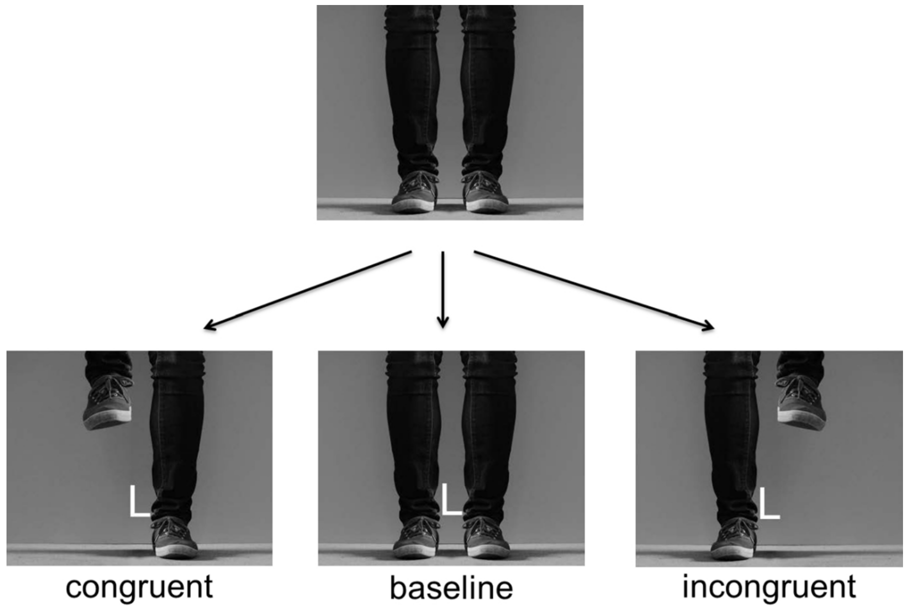

Fig. 1. Illustration of the symbol cue condition of the foot lift experiment. At the beginning of the trial, the lower part of two legs was displayed. After a variable interval, a symbolic cue (L or R) was shown between the two ankles. This could be accompanied by a congruent or incongruent foot lift movement (lower left and right panel), or by no movement (baseline, lower center).

Kinematic and force plate data for each trial were lowpass-filtered using bidirectional Butterworth filter (cut-off frequency 20 Hz, order 5). The foot lift time was determined as the first time point at which the vertical force of one of the force plates dropped below 10 N. Preparatory weight shifts (PWS) were defined based on the GRF difference between the two feet, as transient positive or negative deflections (by more than 5% BW) relative to GRF difference at the beginning of the trial. A *PWS error* was scored when the deflection was inconsistent with the required response. PWS onset times were defined by the first sample in which the GRF deflection exceeded 5% BW. The time interval between (first) PWS onset and foot lift was around 500 ms on average, and below 1000 ms in all analyzed trials. Toe lift and trunk roll amplitude were assessed as control measures. More details can be found in a previous publication [16].

2.5. Statistical analysis

Statistical analyses were performed in R [22]. Dependent variables (foot lift latency, PWS errors) for the *symbol cue* condition of the foot lift experiment were submitted to a repeated measures ANOVA with between-subject factor Age Group (young, older) and within-subject factor Compatibility (congruent, baseline, incongruent). Foot lift and PWS onset times were also analyzed using a repeated measures ANOVA with between-subject factor age group and within-subject factors Compatibility and PWS error (PWS error, no PWS error) or PWS (First, Last).

Performance in balance, cognition, and questionnaire measures (Table 1) was compared between age groups by means of two-sample t-tests. Compatibility effects in the foot lift and Flanker task were quantified by the performance difference between congruent and incongruent trials. Baseline performance and compatibility effects in the foot lift task were tested for correlations with balance performance (one-leg standing with open or closed eyes) and Flanker compatibility effects.

The threshold for statistical significance was 0.05. Significant effects in the ANOVA were followed up by paired t-tests corrected for multiple comparisons (p_{corr}) [23]. Effect sizes are reported as generalized eta-squared scores η^2 [24].

3. Results

3.1. Foot lift task

As our previous research [16] and preliminary analysis of the present data found pronounced compatibility effects only for symbolic cues, we focus on these results. Data from the *movie cue* condition are displayed in Fig. 2 (broken lines) and full statistical analyses are reported as Supplementary Data.

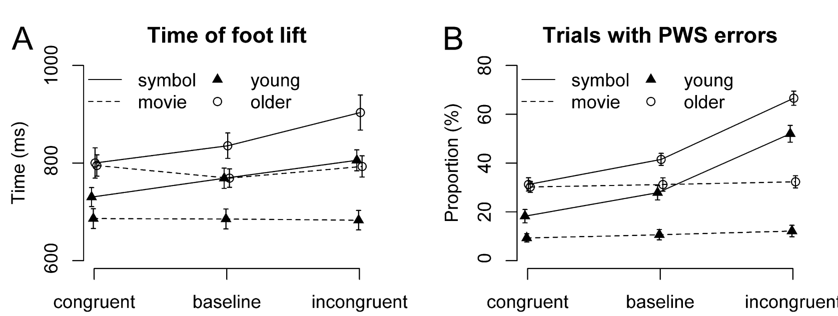

Fig. 2. Main outcome measures for the foot lift experiment as a function of age group, stimulus-response compatibility (congruent, baseline, incongruent) and cue type (symbol, movie; only results from the symbol cue condition are reported in the manuscript): time of foot lift (A), proportion of trials with PWS error (B). Error bars indicate between-subject standard error.

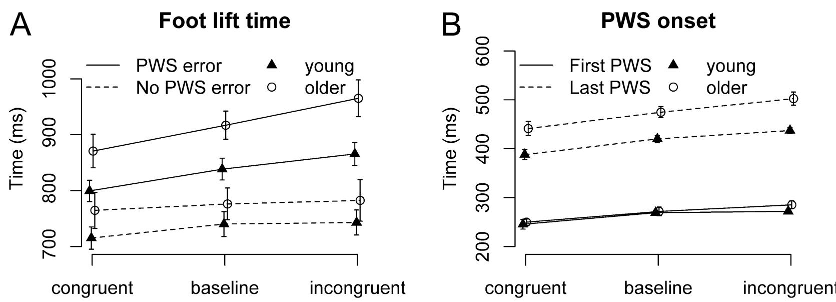

Fig. 3. (A) Foot lift times as a function of age group, stimulus-response compatibility, and presence of PWS error. (B) Onset of the first and last PWS in trials with PWS errors, as a function of age group and stimulus-response compatibility.

For foot lift latency (Fig. 2A), we found main effects of Age Group, F(1,30) = 4.66, $p = 0.039, \eta^2 = 0.13$, and Compatibility, $F(2,60) = 61.8$, $p < 0.001$, $\eta^2 = 0.11$. The PWS error rate (Fig. 2B) showed main effects of Age Group, $F(1,30) = 30.8$, $p < 0.001$, $\eta^2 = 0.27$, and Compatibility, $F(2,60) = 79.8$, $p < 0.001$, $\eta^2 = 0.63$. Older adults had longer foot lift latencies and made more PWS errors than young adults. Moreover, in both age groups, the foot lift latencies were longer and the number of PWS errors was larger for incongruent compared to baseline, and for baseline compared to congruent stimuli ($p_{corr} < 0.01$). Direct assessment of compatibility effects (incongruent-congruent) confirmed the absence of any effects of age groups (Table 1). In order to assess comparability of starting conditions and movement performance, the same ANOVA (Age Group x Compatibility) was performed with several control measures: asymmetry of weight distribution at the time of cue presentation, vertical range of toe, and angular range of trunk movement. None of these showed any main or interaction effects of Age Group.

To scrutinize the effect of PWS errors on response speed, we also assessed whether effects of stimulus-response compatibility and age group on foot lift times differed between trials with and without PWS errors. For foot lift times (Fig. 3A), we found main effects of PWS error, $F(1,30) = 310.2$, $p < 0.001$, $\eta^2 = 0.26$, and Compatibility, $F(2,60) = 34.9$, $p < 0.001$, $\eta^2 = 0.04$, as well as significant interactions of PWS error with Age Group, $F(1,30) = 8.91$, $p = 0.006$, $\eta^2 = 0.01$, and Compatibility, $F(2,60) = 13.2$, $p < 0.001$, $\eta^2 = 0.01$. There was a larger difference in foot lift time between older adults and young adults when errors in APA were made, compared with trials when no errors were made. A post hoc analysis of the interaction effect revealed a significant Age Group effect only for trials with PWS error, $F(1,30) = 6.09$, $p = 0.02$, $\eta^2 = 0.15$, but not for trials without PWS error, $F(1,30) = 1.18$, $p > 0.1$. Following up on the Compatibility x PWS Error interaction, the difference between congruent and incongruent trials was more pronounced in trials with PWS error, mean (SD) 80.3 (58.7) ms, compared to trials without PWS error, 22.9 (38.2) ms, $t(31) = 5.05$, $p < 0.001$.

We also assessed to what extent PWS errors are related to premature response initiation, by comparing the onset of the first PWS in trials with versus without preparation error. This analysis revealed main effects of Compatibility, $F(2,60) = 16.5$, $p < 0.001$, $\eta^2 = 0.06$, and PWS error, $F(1,30) = 47.2$, $p < 0.001$, $\eta^2 = 0.20$, but no significant effects of or interactions with Age Group. First PWS onset occurred indeed earlier in trials with preparation errors, 265.6 (22.5) ms, compared to trials without preparation error, 301.0 (38.8) ms.

The influence of age and stimulus-response compatibility on PWS timing was further investigated in trials with multiple PWSs, comparing onset times for the first versus last PWS (Fig. 3B). This analysis revealed main effects of Age Group, $F(1,30) = 10.7$, $p = 0.003$, $\eta^2 = 0.16$, and Compatibility, $F(2,60) = 37.0$, $p < 0.001$, $\eta^2 = 0.19$, a trivial effect of first vs. last PWS, as well as significant interactions of PWS Error with Age Group, $F(1,30) = 19.9$, $p < 0.001$, $\eta^2 = 0.11$, and Compatibility, $F(2,60) = 8.39$, $p < 0.001$, $\eta^2 = 0.18$. The effect of age group was more pronounced for the last than for the first PWS. Indeed, restraining the ANOVA revealed a significant effect of Age Group only for the last PWS, $F(1,30) = 17.02$, $p = 0.003$, $\eta^2 = 0.31$, but not for the first PWS, $F(1,30) = 0.72$, $p > 0.1$. The difference between incongruent and congruent trials was more pronounced for the last PWS, mean (SD) 55.1 (39.5) ms, compared to the first PWS, 31.3 (33.8) ms, $t(31) = 3.82$, $p < 0.001$.

3.2. Balance, cognitive control, and correlational analysis

Due to equipment failure, no data are available for the Flanker task from one young subject. Older adults had lower performance in one-leg standing and lower response accuracy in the Flanker task (Table 1). Compatibility effects (incongruent–congruent) for foot lift latency and Flanker accuracy (Fig. 4) were significantly correlated in older adults (*rho* = –0.65, $p = 0.006$), with stronger interference in one task being associated with stronger interference in the other task, but not in young adults (*rho* = 0.15, $p > 0.5$). Other correlations of balance or Flanker performance with mean performance or compatibility effects in the foot lift task were not significant ($p > 0.1$ in all cases).

4. Discussion

We investigated performance differences between young and older adults in a two-choice response task with balance constraints and different levels of response conflict (stimulus-response compatibility). Our main findings were: (1) Older adults showed delayed responses and increased number of preparatory weight

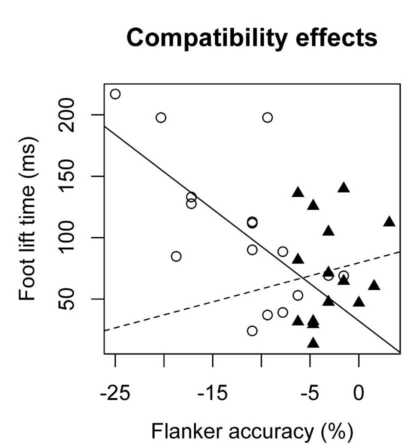

Fig. 4. Relation between interference scores (incongruent–congruent) in the foot lift and Flanker tasks, for young (filled triangles, dashed regression line), and older adults (open circles, continuous regression line).

shift (PWS) errors compared to younger adults; (2) older and younger adults showed comparable compatibility effects; (3) effects of age and stimulus-response compatibility on response times were strongly reduced or absent when constraining the analysis to trials without PWS errors, or to the first PWS in trials with PWS errors; (4) in older adults, compatibility effects were significantly correlated between the foot lift and the Flanker task.

Adult age differences in PWS errors and response latencies have previously been studied in related tasks, such as gait initiation and stepping movements [13–15]. This study extends these results, showing that age-related increases in preparatory errors also occur for the simpler task of lifting one foot from the floor. This relatively simple task may explain why we did not find age-related amplification of compatibility effects. For instance, Sparto et al. [15] combined a lateral stepping task with a relatively wide stance position with a spatial stimulus-response conflict paradigm, finding greater compatibility effects in older compared to younger adults. In that study, older adults also showed a larger variety of postural preparation strategies than young adults. While this finding is important by itself, a simpler task, as used in this study, may be preferable in order to scrutinize the relation between PWS errors and response latencies.

Automatic imitation tendencies, that is, facilitation of movements which are compatible with an observed movement and degradation of incompatible movements, have been studied to great extent in young adults and children [25], but to our knowledge this is the first study with adults in later periods of adulthood (59–73 years). In this study, response conflict (induced by stimulus-response compatibility) led to increased response latencies and PWS errors in both age groups, and compatibility effects did not reliably differ between the age groups. Presence of automatic imitation tendencies in both age groups is further demonstrated by faster responses in the movie cue compared to the symbol cue condition (reported in supplementary material).

Effects of age and stimulus-response compatibility on response timing were strongly reduced or even absent when constraining the analysis to trials without preparation errors, or to the first PWS in trials with preparation errors. This strongly suggests that age differences found for the foot lift response times are not due to general slowing alone [26], but may rather be explained by erroneous response preparation. Moreover, the fact that response conflict had only minimal effects on the onset of the first PWS (in trials with preparation error) indicates that it was not resolved at a purely cognitive level, but affected motor performance while cognitive processing was still ongoing [16]. It has been argued that response selection (here: moving the correct foot) and response inhibition (preventing a prepotent, automatic response) relies on overlapping neural mechanisms [27]. The parallel findings in this study regarding the influence of age and response conflict suggest that age comes with an increased difficulty in response selection, which may be related to insufficient inhibition of the alternative (wrong) response [13].

PWS errors can be considered as partial errors, that is, covert activation of alternative responses [28–30] which can be corrected before the actual response. Surprisingly, potential effects of normal aging on partial errors appear to have received limited scientific attention. Two previous age-comparative studies using *manual* response paradigms did not find systematic differences between older and younger adults in the frequency of partial errors [31,32]. Age-differences in PWS errors in the foot lift task used here or in stepping tasks used in previous studies [13,15] may therefore be due to postural stability requirements. However, in this study, poorer performance in the foot lift task was not associated with balance skill (one-leg standing) but with stronger interference effects in the Flanker task, corroborating the role of cognitive control in this paradigm.

Summing up, the present results generalize the effect of stimulus-response compatibility effects in a task with balance constraints [16] to a sample of older adults. Moreover, the results extend previous studies on the effect of response conflict on balance performance in older adults [13–15]. Our findings provide strong evidence that adult age differences in response latency in a task with balance constraints are not entirely explained by general slowing but are at least partially due to increased postural preparation errors.

Author note

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Conflict of interest statement

The authors declare no actual or potential conflict of interest.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gaitpost.2015.12.002.

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