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BRIEF REPORT

# Age Differences in Processing Fluctuations in Postural Control Across Trials and Across Days

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Postural control performances of 18 younger and 18 older adults were repeatedly measured on 45 weekdays with five trials per day. This design made it possible to dissociate between long-term trends and processing fluctuations in the sensorimotor domain at moment-to-moment, trial-to-trial, and day-to-day levels. Older adults fluctuated more than younger adults at all timescales. Age differences in trial-to-trial and day-to-day processing fluctuations were reduced but remained statistically significant when controlling for fluctuations on faster timescales. We concluded that age differences in intraindividual fluctuations at the longer timescales are in part related to age differences in low-level system robustness, suggesting a cascade of effects across multiple timescales.

*Keywords:* intraindividual variability, motor performance, methods, microlongitudinal design

Processing fluctuations are inherent features of any system that involves multiple subsystems, multiple control mechanisms, and dynamic interactions between the organism and the environment (Port & Geldern, 1995). A lack of processing robustness of such systems can be reflected in maladaptive process fluctuations on relatively short timescales like trials, days, or weeks (Li, Huxhold, & Schmiedek, 2004). The research on age-related increases of processing fluctuations in cognitive performances has gained increasing momentum during recent years (Hultsch, MacDonald, Hunter, Levy-Bencheton, & Strauss, 2000; Li, Huxhold, & Schmiedek, 2004; Lindenberger & von Oertzten, 2006; MacDonald, Nyberg, & Bäckman, 2006; Nesselroade & Salthouse, 2004). This study investigates adult age differences in processing fluctuations in the sensorimotor domain, focusing on postural control. Postural control is specifically suited for the investigation of intraindividual variability, because the main task of the postural control system is the minimization of processing fluctuations (i.e., body sway) to maintain the upright stand. Moreover, the effective maintenance of the body's balance is a necessary prerequisite for independent living in old age, whereas the flip side, falls caused by losses of balance, bear severe consequences on the elderly population (Brown & Woollacott, 1998; Lord, Clark, Williams, & Anstey, 1993; Sattin, 1992; Woollacott, 2000). Postural control is a highly automatized task that involves complex, dynamic interactions between sensorimotor and cognitive processes (Donker, Roerdink, Greven, & Beek, 2007; Fraizer & Mitra, 2008; Huxhold, Li, Schmiedek, & Lindenberger, 2006; Manchester, Woollacott, Zederbauer-Hilton, & Marin, 1989; Schäfer, Huxhold, & Lindenberger, 2007; Woollacott & Shumway-Cook, 2002). The brain utilizes internal representations of motor commands and multisensory feedbacks to monitor, update, calibrate, and maintain the body's position (Mergner & Rosemeier, 1998). Aging is associated with declines in basically all subsystems involved in postural control (Maki & McIlroy, 1996; Woollacott, 2000). These losses attenuate the harmonic interplay between the constituent subprocesses of postural control and limit the temporal dynamic com-

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plexity of postural control processes (Lipsitz, 2002). Senescent changes in postural control hinder the fast and accurate execution of an appropriate response to a given disturbance to the body's balance, thereby leading to maladaptive responses that result in a greater extent of body sway. We define disturbance in a broad sense that encompasses a number of circumstances exerting negative influences on the postural control system. These include conditions that hamper one or several of the constituent processes or the interplay between these processes. Disturbances can occur on different time scales and can have more or less lasting effects. For example, intraindividual variations in cognitive resources from one minute to the next could hamper the accurate processing of sensory information necessary for balance control. Momentary variations in the sensorimotor components of postural control (e.g., Mendelson, Redfern, Nebes, & Jennings, 2010) may demand more top-down regulations in order to keep balance. Still, variations in the quality of sleep might affect both attentional and sensorimotor components and result in fluctuations in the efficiency of the postural control system from one day to the next. All of these kinds of disturbances have in common that the postural control system is bound to adapt to them to maintain functioning. Newell and colleagues (Sosnoff & Newell, 2006; Vaillancourt & Newell, 2002) argued that older adults have specific difficulties to adjust their postural control system to task requirements. It has also been suggested that disruptions in the dynamic interplay of subsystems imply an inability of an aged system to detect small disturbances (Thaler, 2002). This latter perspective is consistent with neurocomputational accounts of aging-related differences in gain control of information processing. According to some of these models (Li, Lindenberger, & Sikstrom, 2001; Li, von Oertzen, & Lindenberger, 2006), aging-induced decrements in signal-to-noise ratio result in less distinctive representations of sensory information. Accordingly, the aging postural control system is increasingly less apt to detect disturbances and progressively less able to initiate accurate responses. Thus, the aged postural control system is less able to balance out disturbances, which then would result in greater processing fluctuations. Andersson and Yardley (2000) found, for example, that the postural control system of older adults is more vulnerable to daily variations in stress than that of younger. Numerous studies have demonstrated that older adults' postural control fluctuates more than that of younger adults from one moment to the next (Choy, Brauer, & Nitz, 2003; Manchester et al., 1989; Woollacott, 2000). The effect of aging on moment-to-moment fluctuations—conventionally called postural sway—increase with task difficulty and mean age differences between groups (Woollacott, 2000). Intraindividual variability on more extended timescales have only rarely been explored so far (Dault & Frank, 2004). The investigation of longer-term fluctuations in the context of aging is, however, important. Variations in postural control performances do not only arise as a result of changing task requirements (e.g., in experimental settings) but also because of disturbances to the system that occur in everyday life. As argued above, older adults are particularly vulnerable to such disturbances.

Not all variability in postural control is maladaptive per se. It can entail exploratory behavior to increase the sensory input or adaptations to task requirements (Sosnoff & Newell, 2006). Most studies, however, interpret increasing amounts of postural sway as dysfunctional. High amounts of postural sway are associated with higher risks of falls and a number of sensorimotor pathologies (Frenklach, Louie, Koop, & Bronte-Stewart, 2009; Lord, Rogers, Howland, & Fitzpatrick, 1999). We argue that moment-to-moment processing fluctuations (i.e., postural sway) can serve as an indicator of low level processing robustness, because—as outlined above—these fluctuations are assumed to be in part direct consequences of internal noise in the postural control system. From this perspective, fast fluctuations can be understood as markers of general vulnerability to disturbances, which can occur on different timescales. Thus, age differences on fast processing fluctuations can also have a cascading effect across multiple timescales. Specifically, older adults can be expected to show higher processing fluctuations than younger adults not only from moment to moment but also from one trial to the next and between days. Furthermore, we expect that age differences in trial-to-trial and day-to-day processing fluctuations would be attenuated after controlling for low-level system robustness, but would still remain, because the vulnerability to factors operating at longer time scales is assumed to be increased with age as well.

# Method

## Sample

The sample consisted of 18 younger adults ($M_{\text{age}}$ = 25.5, $SD_{\text{age}}$ = 2.73) and 18 community-dwelling older adults ($M_{\text{age}}$ = 74.19, $SD_{\text{age}}$ = 2.84) who took part in the Intra-Person Dynamics Project's Daily Fluctuation Study conducted at the Max Planck Institute for Human Development (Lindenberger, Li, Lovden, & Schmiedek, 2007). In this study, a large battery of emotional, motivational, cognitive, and physiological variables were assessed. All participants underwent an intensive baseline assessment distributed over three days, in which they were introduced to and familiarized with the tasks. Upon completing the baseline assessment, participants' postural control performances were repeatedly assessed on 45 consecutive weekdays. Assessments were carried out for every individual at the same time on each day. In accordance with the results of studies of age differences in time-of-day effects (Hasher, Chung, May, & Foong, 2002) most older participants in our study were tested at the same time every morning and most younger adults were assessed in the afternoon. Thus, results of the analyses could only be minimally biased by time-of-day effects. On average, participants underwent 44.7 daily assessments. No reliable age differences in participation rate were observed. No participant reported any balance-related health problems or any age-related neurological and psychiatric diseases.

## Postural Control Measures

The participants' dynamic posturography was measured with a force platform (60 cm × 40 cm; Kistler platform 9286AA, Kistler Instrumenten AG, Winterhur, Switzerland) that was connected to a high-speed measurement computer (μ-MUSYCS; m-M-S_ Eth-RJ45). Twelve sensors built into the force platform measured medio-lateral, anterior-posterior, and vertical components of ground reaction forces and momentums. Their signals were sampled at a rate of 80 MHz, and *x-y* coordinates of center of pressure (COP) positions for every millisecond were calculated. Postural control was indexed by the area traveled by the COP in a trial lasting 68 seconds. We chose COP-area as an absolute measure of postural sway, because COP-area has been shown to be a very reliable measure that is highly sensitive to experimental manipulations and age effects (e.g., Huxhold et al., 2006; Raymakers, Samson, & Verhaar, 2005). Participants were instructed to stand as still as possible while maintaining a semitandem stand that was adjusted to the individual's sway in shoulder-width stand. Specifically, participants started out with a full tandem stand (one foot in direct line before the other) and step-by-step moved the front foot to the side of the other foot (toward parallel stand) until the COP area was approximately 2.5 times as large as the COP area in parallel stand. Pilot testing showed that this procedure results in a condition that is manageable for older adults to maintain for 68 seconds without showing step reactions or signs of exhaustion. While the task was difficult, it therefore still allowed the measurement of postural stability across each trial in a stationary manner. This procedure also balanced interindividual differences in standing difficulty.

Processing fluctuations on extended timescales have to be distinguished from intraindividual variability caused by learning (Li, Huxhold, & Schmiedek, 2004). Therefore, learning trends in postural control performances were extracted from the data before processing fluctuations were analyzed. Postural control was measured on 45 days with five trials per day. To identify outliers in a way that accounts for trends in the data, a flexible, nonparametric loess curve (Cleveland & Devlin, 1988) was estimated across all trials of assessments separately for every participant. Individuals' trials with area values above four intraindividual standard deviations of the value predicted by the loess function were dismissed. Less than 1.5% of all trials were identified as outliers. The average area across the 45 days of assessment served as an index of moment-to-moment fluctuations. In concordance with results of training studies, no learning trends were observable within days in postural control (Dault & Frank, 2004). A standard deviation was calculated across the five trials for every day and every participant. The average standard deviation of trials across the 45 days of assessment indexed trial-to-trial fluctuations. Across days, postural control performances demonstrated long-term trends. The absolute residuals around individualized trend curves indexed day-to-day processing fluctuations.

## Statistical Analyses

**Trend analysis.** Multilevel models were used to examine the influence of learning on the overall intraindividual fluctuation in postural control. Learning gains were observable across the 45 days of assessment but not within days. Visual inspection of the daily postural control performances revealed that no single theoretical function (e.g., exponential learning) could account for the interindividual differences in these trends. Therefore, polynomials of increasing order were fitted to the data with multilevel models to parsimoniously describe average trends and interindividual differences in trends. Next, trends were individually partialed out from the daily postural control data.

**Analyses of processing fluctuations.** Moment-to-moment fluctuations served as indicators for low-level system robustness and were analyzed with a univariate ANOVA with age group as two-level, between-subjects factor. Subsequent analyses aimed not only at the examination of age differences on extended timescales but also examined the influence of low-level processing robustness on fluctuations on these scales. This influence was examined using a within-person approach in the sense that moment-to-moment fluctuations were partialed out from processing fluctuations on the extended timescales separately for every participant. Recently, Schmiedek and colleagues (Schmiedek, Lovden, & Lindenberger, 2009) have shown that the strength of the relationship of mean performances and variability in reaction time differs between persons. Intraindividually regressing slower fluctuations on faster fluctuations, considers interindividual differences in the relationship between faster and slower processing relations in a similar manner as the Schmiedek, Lovden, & Lindenberger (2009) approach. Such a method also prevents spurious age correlations from affecting the observed effect sizes. For every participant, 45 daily estimates of trial-to-trial fluctuations were regressed on the 45 daily estimates of moment-to-moment fluctuations. In a similar vein, the individual's day-to-day fluctuations were averaged within weeks and regressed on their weekly averages of moment-to-moment sway and trial-to-trial fluctuations. The residuals of these regressions were saved and served as indicators of trial-to-trial fluctuations and day-to-day fluctuations independent of the influence of the influences of fluctuations on faster timescales. Two repeated-measures ANOVAs were separately conducted for trial-to-trial and day-to-day fluctuations with controlling for faster fluctuations versus no controlling for faster fluctuations as a within-subject factor and age group as a between-subjects factor to examine whether age differences would be attenuated after controlling for the influence of lower-level system robustness. An interaction between age group and control indicates that the reduction in intraindividual variability attributable to controlling for processing fluctuations on faster time scales varied by age group. Planned contrasts evaluated whether age differences remained significant in long-term fluctuations after controlling. Significance tests ($\alpha$ level set to $p < .05$) and eta square values are reported. To eliminate the possibility that age differential links of variability in postural control on different time scales is simply a by-product of age differences in cognitive performances, we additionally controlled for interindividual differences in perceptual speed measured with the digit-symbol-substitution and the identical pictures tests. The results thus obtained were in terms of statistical significance identical.

# Results

## Trend Analyses

The results and the parameter values of the multilevel analysis of trends in postural control performance are shown in Table 1. Multilevel models dissociate the overall variability into fixed effects indicating average performance and random effects indicating interindividual differences in these parameters. Linear and quadratic trends in the data and interindividual differences around these were tested with $\chi^2$-difference tests. Moment-to-moment processing fluctuations decreased significantly on average by 54.72 $mm^2$ across the 45 days of assessments [$\gamma_{10}$, $\chi^2(1) = 104$; $p < .05$]. The significant quadratic term [$\gamma_{20}$, $\chi^2(1) = 10.8$; $p < .05$] showed that learning gains were, on average, more pronounced at the beginning of the assessment and leveled off toward the end. Significant interindividual differences were found in the

Table 1
*Multi-Level Estimation of Trends in Postural Control Performances Across 45 Days*

| | Parameter | Value | Model change |
|---|---|---|---|
| Fixed effects | | | |
| Average | | | |
| Intercept | $\gamma_{00}$ | 145.82 | |
| Age | $\gamma_{01}$ | 200.51 | $\chi^2(1) = 12; p < .05$ |
| Linear | | | |
| Intercept | $\gamma_{10}$ | −54.72 | $\chi^2(1) = 104; p < .05$ |
| Age | $\gamma_{11}$ | | $\chi^2(1) = 0.2; p < .05$ |
| Quadratic | | | |
| Intercept | $\gamma_{20}$ | 65.42 | $\chi^2(1) = 10.8; p < .05$ |
| Age | $\gamma_{21}$ | | $\chi^2(1) = 0.1; p > .05$ |
| Random effects (variance components) | | | |
| Level 1 | | | |
| Within-person | $\sigma^2_\epsilon$ | 3017.02 | |
| Level 2 | | | |
| In average | $\sigma^2_0$ | 25215 | |
| In Linear | $\sigma^2_1$ | 3644.43 | $\chi^2(1) = 79.6; p < .05$ |
| In Quadratic | $\sigma^2_2$ | 32318 | $\chi^2(1) = 45.6; p < .05$ |
| In Linear by Quadratic | $\sigma_{21}$ | −6246.35 | $\chi^2(1) = 7.7; p < .05$ |

*Note.* Age = age group effect; Linear = linear trend; Quadratic = quadratic trend.

linear slope parameter [$\sigma^2_1$, $\chi^2(1) = 79.6$; $p < .05$] as well as in the quadratic curvature parameter [$\sigma^2_2$, $\chi^2(1) = 45.6$; $p < .05$]. The shape of the trends in postural control did not differ systematically between age groups. Older adults profited on average as much as the younger adults from the repeated testing sessions. Figure 1 displays trends and processing fluctuations in postural control separately for both age groups.

## Analyses of Processing Fluctuations

**Moment-to-moment fluctuations.** As can be seen in Figure 2a, older adults fluctuated on average more from one moment to the next than younger adults. The effect of age group on moment-to-moment sway was significant, $F(1, 34) = 14.36$, $p < .05$, $\eta^2 = .30$.

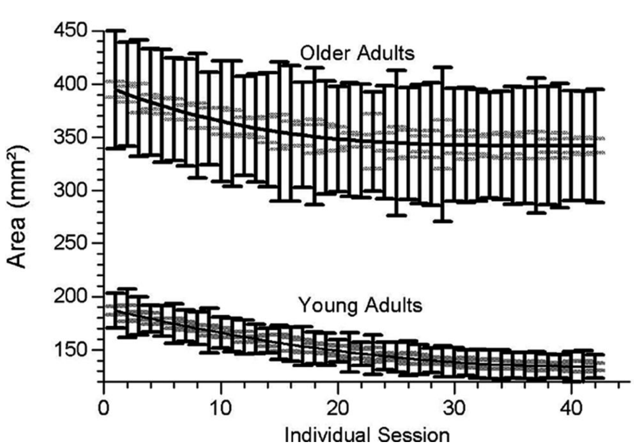


*Figure 1.* Average trends and processing fluctuations in postural control performances across 45 days by age group. Postural control performance measured in area (mm$^2$). Black error bars represent between-person differences in moment-to-moment sway. Gray error bars index between-person differences in intraindividual day-to-day fluctuations.

**Trial-to-trial fluctuations.** We found significant effects of age group, $F(1, 34) = 13.26$, $p < .05$, $\eta^2 = .28$, controlling for moment-to-moment sway, $F(1, 34) = 93.30$, $p < .05$, $\eta^2 = .66$, and of the interaction between age group and controlling for momentary sway, $F(1, 34) = 13.05$, $p < .05$, $\eta^2 = .09$. Older adults were more variable in their postural control performance than younger adults. The significant age-by-momentary sway interaction indicated that age differences were reduced by the within-person control of moment-to-moment fluctuations. Trial-to-trial fluctuations of older adults were more strongly influenced by moment-to-moment low level processing robustness than that of younger adults (see Figure 2b). Age differences in trial-to-trial fluctuations remained significant after controlling for momentary sway, $F(1, 34) = 12,87$, $p < .05$, $\eta^2 = .28$.

**Day-to-day fluctuations.** The effects of age group, $F(1, 34) = 17.46$, $p < .05$, $\eta^2 = .34$, and controlling for faster fluctuations, $F(1, 34) = 114.52$, $p < .05$, $\eta^2 = .70$, and the interaction between age group and controlling for faster fluctuations, $F(1, 34) = 15.27$, $p < .05$, $\eta^2 = .09$, were significant. Older adults' postural control fluctuated more from day to day than the performances of younger adults. The significant interaction term indicated that the age difference in the day-to-day component of postural sway was reduced after intraindividually controlling for faster fluctuations (see Figure 2c). Age differences in day-to-day fluctuations remained significant after controlling for faster fluctuations, $F(1, 34) = 13.37$, $p < .05$, $\eta^2 = .28$.

## Discussion

With advancing age, older adults experience declines in the efficiency of subsystems regulating the body's equilibrium (Woollacott, 2000; Maki & McIllroy, 1996). In our study, the participants' balance was challenged by our experimental manipulation and thus older adults showed significantly more moment-to-moment fluctuations (i.e., postural sway) than younger adults. The amount of sway was reduced by learning across the 45 days of

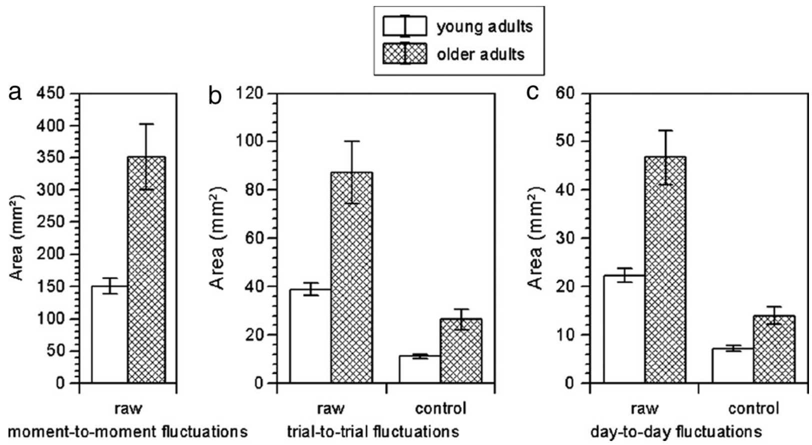


*Figure 2.* Age differences in processing fluctuations on multiple timescales. a, Moment-to-moment fluctuations (area/mm$^2$). b, Trial-to-trial fluctuations (area/mm$^2$). c, Day-to-day fluctuations (area/mm$^2$). raw = raw scores. control = raw scores intraindividually controlled for fluctuations on faster timescales.

testing; the age difference, however, remained significant at all daily assessments (see Figure 1) and explained approximately 30% of the total variance. More importantly, older adults showed more pronounced processing fluctuations in their performances than younger adults from trial to trial and also from day to day. To illustrate the strength of the trial-to-trial and day-to-day processing fluctuations, we adapted an approach from Nesselroade and Salthouse (2004). We compared trial-to-trial and day-to-day processing fluctuations in the older age group with the age difference in basic postural sway. The difference in age between the two groups was 48.7 years, and the difference in moment-to-moment fluctuations was about 200 mm$^2$. Assuming that the age effect on postural control is roughly linear, it follows that the average of 87 mm$^2$ that the older group fluctuated between trials equals an age difference of 21 years. This means that a 74-year-old older participant could perform on average on *any given trial* like a person of 53 years. Similarly, the same older participant could on average perform at *any given day* like a person of 62 years. These findings are not trivial. In the cognitive domain, the likelihood of significant age differences in processing fluctuations is a function of task complexity. Age differences in terms of processing fluctuations are often absent in easy cognitive tasks (Roberts & Pallier, 2001; West, Murphy, Armilio, Craik, & Stuss, 2002). Bearing these results in mind, the significant age effects in processing fluctuations on extended timescales argue for the high coordinative complexity of posture regulation. Apparently, the harmonic meshing of sensory, motoric, and cognitive processes, necessary for efficient postural control, is disturbed by senescent changes. These disturbances lead to an aging-associated increase in processing fluctuations on multiple timescales. Moreover, this study demonstrated that age-differences in trial-to-trial and day-to-day fluctuations are significantly influenced by low-level processing robustness. A significant amount of the observed age differences on both extended timescales could be accounted for by intraindividually controlling for processing fluctuations on faster timescales. Controlling for low level processing robustness reduced the absolute size of the age difference in trial-to-trial fluctuations by 68.4% and the size of age difference in day-to-day fluctuations by 73.2% (see Figure 2).

Most models of motor control predict that performances depend on the accurate internal representation of sensory information (Mergner & Rosemeier, 1998; Wolpert, Ghahramani, & Flanagan, 2001). The accuracy of the internal representation of the body and the environment is important to estimate the sensory consequences of motor commands (i.e., forward control) and for the internal computation of motor commands to achieve desired sensory outcomes (i.e., inverse control) (Wolpert, Ghahramani, & Flanagan, 2001). Neuro-computational models have predicted decreasing distinctiveness of sensorimotor representations in older adults (e.g., Li, Lindenberger, & Sikstrom, 2001; Li, von Oertzen, & Lindenberger, 2006) Moreover, age related declines in dopaminergic neuromodulation have been suspected to increase the internal noise in sensorimotor control (e.g., Li, Lindenberger, & Sikstrom, 2001; Li, von Oertzen, & Lindenberger, 2006). Experimental evidence linking the amount of postural sway to striatal dopamine denervation in normal aged adults and the high vulnerability of older adults with Parkinson's disease to disturbances to their sensorimotor system (Cham, Perera, Studenski, & Bohnen, 2007; De Nunzio, Nardone, & Schieppati, 2007) seem to support the idea that senescent losses in neuromodulation are important causes of age differences in processing fluctuations in sensorimotor control. Our data also suggest further that factors affecting mechanisms on faster timescales—like the decreasing distinctiveness of sensorimotor representations—may lead to a cascading effect on processes on slower timescales by creating an increased vulnerability to time-scale specific disturbances. Low level system robustness hampers adaptive responses to disturbances to the postural control system occurring in everyday life from one minute to the next or from one day to the next.

Postural control performance is commonly assessed with a few trials within a single assessment session. The results of this study show that these assessments are less reliable for older adults than for young adults. Furthermore, it seems plausible that falls do not happen if the postural control system works with its average capacity but occur in situations when the system is challenged (LundinOlsson, Nyberg, & Gustafson, 1997). Consequentially, the amount of processing fluctuations on slower timescales may be a better indicator of how often the postural control system is in a vulnerable state than measures of average postural sway. Thus, further studies should evaluate the predictive value of long-term fluctuations with respect to falls.

One limitation of our study is, however, that the COP-measures we could use were for technical reasons bound to be measures of COP-dispersion. Age effects could have been even more dramatic if we would have been able to link processing fluctuations to the potential area of stable support, which is also reduced with age.[1] Future studies could use dynamic system analyses like wavelet analyses to explore the temporal nature of the effects of disturbances on the moment-to-moment level to identify the specific mechanisms that are affected (e.g., open loop or close loop control processes; (Chagdes et al., 2009). With regard to intervention it is, however, even more important to identify potential sources of disturbances to the postural control system working on extended time scales. Promising candidates in this regard are fluctuations in cognitive performances. Older adults direct more attentional resources to their postural control system to counteract the adverse effects of the deprived distinctiveness of their sensory representations. In this regard, dual-task studies have demonstrated that older adults rely more than young adults on cognitive processing in their sensorimotor performances (Li & Lindenberger, 2002). Furthermore, fluctuations in sensorimotor performances have been found to predict cognitive performances in older adults (Li, Aggen, Nesselroade, & Baltes, 2001).

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