# 6. General Discussion

This chapter begins with a brief summary of the empirical findings that speak to the main hypotheses of this dissertation. Following the summary, the findings are then discussed in more detail with respect to a few, as yet unresolved issues in the research on individual differences in processing variability.

## 6.1 Summary of Empirical Findings

Hypotheses 1 to 3 of this dissertation predicted that older adults would exhibit more processing fluctuations from moment-to-moment (Hypothesis 1), trial-to-trial (Hypothesis 2), and day-to-day (Hypothesis 3). A clear finding of this study is that older adults showed more pronounced moment-to-moment processing fluctuations in postural control than young adults, regardless of whether fluctuations were indicated by baseline postural sway or by the average sway across 45 days. Moreover, older adults demonstrated more fluctuations between trials and fluctuated more from one day to the next than young adults. However, age differences in trial-to-trial fluctuations were no longer significant if interindividual differences in postural sway were taken into account. Age differences in day-to-day fluctuations remained significant if interindividual differences in postural sway at baseline were statistically controlled, but were no longer significant after controlling for interindividual differences in the average sway across the daily assessments. These results indicate that processing fluctuations on longer time scales might be functionally related to processing fluctuations at the moment-to-moment level. However, an individual-based analysis demonstrated that the within-person relationships between processing fluctuation at the moment-to-moment scale and the trial-to-trial scale differed significantly between persons. Moreover, age differences in trial-to-trial fluctuations remained significant after controlling for the within-person relationships between postural sway and trial-to-trial fluctuations. These divergent findings are discussed in Section 6.2.3.

Hypotheses 4 to 6 predicted a general advantage of women over men in terms of lower levels of processing fluctuations from moment-to-moment (Hypothesis 4), trial-to-trial (Hypothesis 5), and day-to-day (Hypothesis 6). However, women showed significantly less processing fluctuations than men only at the moment-to-moment level. This effect of sex did not interact with age. Sex differences were not significant in trial-to-trial and day-to-day fluctuations in postural control. As an interpretation, it is argued in Section 6.3 that the female advantage in postural control is most likely to be due to stable anthropomorphic sex differences.

In line with Hypothesis 7, processing fluctuations in postural control were on average significantly related to processing fluctuations in WM. However, the results of this study could not directly confirm Hypotheses 8 and 9. Neither age group, nor sex, nor the interaction of age and sex significantly predicted interindividual differences in the intraindividual cross-domain couplings. Instead, in line with predictions from the cognitive permeation hypothesis, the strength of the intraindividual cross-domain couplings was modulated by interindividual differences in the average level of postural control. The average level of WM performance or the interaction between the average levels of postural control and working memory did not affect the strength of the cross-domain couplings. In Section 6.4.4, it is discussed why interindividual differences in average postural control performance but not age group differentiated between within-person cross-domain couplings of differing strengths. A follow-up analysis showed that the within-person relationship between processing fluctuations in postural control and working memory was significantly more positive in older men than in all other participants taken together.

## 6.2 Age Differences in Processing Fluctuations of Postural Control

This dissertation examined three hypotheses predicting significant age differences in processing fluctuations in postural control on three time scales. More specifically, processing fluctuations occurring from moment-to-moment, which are at the level of common measures of postural sway, between repeated trials, and across different days were investigated. It was hypothesized that due to declines in various mechanisms of their postural control system older adults would exhibit more processing fluctuations than young adults on all three time scales.

### 6.2.1 Age Differences in Moment-to-Moment Processing Fluctuations

Postural control results from complex interactions of sensory, motoric, and cognitive processes, which involve executive functions at least under certain circumstances (K. Z. H. Li & Lindenberger, 2002; Schäfer et al., in press). During senescence, older adults experience declines in the efficiency of basically all subsystems involved in the regulation of the body's equilibrium (Maki & McIllroy, 1996; Woollacott, 2000). However, notable decreases in performance in simple standing occur relatively late in adult development (Choy et al., 2003; Maylor et al., 2001). In most daily situations, postural control is mostly executed with full availability of relevant sensory input (i.e., proprioceptive, vestibular, and visual information) and firm standing positions. Under these stable non-challenging conditions, age differences in postural control can only be found when contrasting young adults with older adults in their seventh decade of life or older (Choy et al., 2003; Maylor et al., 2001). These findings point to the fact that although postural control is a complex process, it is also a highly overlearned and automatized task. Even in their seventies, most older adults spent sufficient amounts of time in daily situations in which they perform the act of keeping the upright stance. An aging-related deficit in postural control becomes, however, more apparent if the sensory or standing conditions are difficult (Choy et al., 2003). Therefore, in the context of this dissertation a relatively old group of adults was chosen (mean age = 74.39 years) and the demand of the standing position was adjusted individually.

It was empirically shown that under the experimental conditions mentioned above older adults showed significantly more moment-to-moment fluctuations (i.e., postural sway) than young adults, which is in accordance with the prediction of Hypothesis 1. This age difference was significant in simple standing and in dual-task standing conditions. Moreover, significant age differences were apparent at the first measurement occasion at baseline and remained significant with respect to the average amount of moment-to-moment fluctuations across all daily assessments. The latter finding is interesting because the daily average performance provides a more accurate and more reliable measure of postural control performances than the single-occasion performance indicators commonly used in the literature. The postural control performance measured at baseline, which was assessed with a few trials on a single day, is equivalent to a regular common postural control indicator used in almost all empirical studies. In contrast, the daily average level of moment-to-moment processing fluctuations is computed from approximately 225 trials distributed over 45 days for each individual in the study. The averaging presumably effectively controlled for measurement errors. The effects of learning and habituation to the experimental environment, however, influenced the values obtained by this aggregation. The possible effect of habituation should not be neglected in this regard since there is some empirical indication in cognitive aging research that age differences in tasks involving executive functioning are specifically pronounced if these tasks are novel (Rabbitt, Lowe, & Shilling, 2001). Nevertheless, older adults showed stronger moment-to-moment processing fluctuations in postural control than younger adults even with respect to the average across the entire daily assessment period. Put differently, age differences in postural sway did not vanish after approximately 45 individual "practice" sessions. This finding is remarkable since it mirrors results obtained in age-comparative studies of higher-order cognitive functions using the Testing-the-Limits paradigm (Baltes & Kliegl, 199; Kliegl, Smith, & Baltes, 1990; Lindenberger & Baltes, 1995; Singer, Lindenberger, & Baltes, 2003). Age differences in postural control at the moment-to-moment level and their antecedences, correlates, and consequences were already relatively well understood. Age differences in processing fluctuations occurring on longer time scales (i.e., across trials or days) have been mostly neglected in the literature thus far.

### 6.2.2 Age Differences in Processing Fluctuations in Postural Control on More Extended Time Scales

Dynamic systems analyses have demonstrated that postural control performance of healthy individuals is characterized by highly complex output patterns (Lipsitz, 2002; Thurner et al., 2002). Complexity in terms of dynamic systems theory denotes the degree of *a priori* information that is necessary to predict the behavior of a system over time. In other words, complexity is determined by the degree to which the system's behavior is unpredictable over time (e.g., Vaillancourt & Newell, 2002). The more complex the pattern the more efficiently does the postural control system work. Empirically, it has been shown that the complexity of postural control is negatively correlated with processing fluctuations in postural control (Thurner et al., 2000). Complexity of a given system is assumed to be achieved by a harmonic, dynamic interaction between different subsystems under the supervision of feedback mechanisms working on multiple time scales (Goldberger et al., 2002). Each input of the sensory systems involved in postural control, for example, can be identified by characteristic rhythm in the change of the postural control signal (Thurner et al., 2000). Lipsitz (2002) argued that these multiple rhythms enable the healthy individual to initiate a focused response to a given perturbation to the system and thus are critical to prevent processing fluctuations. Senescent changes in the postural control systems of aging adults are assumed to lead to a reduction in the system's complexity (e.g., Goldberger et al., 2002). According to the theory of loss of complexity, these losses render the system of older adults to be less robust against disturbances and thus lead to a higher amount of processing fluctuations (Lipsitz, 2002). Furthermore, Thaler (2002) suggested that older adults would have more difficulties to actually detect perturbations to their systems than young adults. This hypothesis is in line with predictions of neural network models suggesting that deficient neuronal modulations lead to less discriminative representations of external stimuli in older adults (S.-C. Li & Lindenberger, 1999; S.-C. Li et al., 2000). Perturbations in systems with less distinctive representation are harder to detect. Therefore, older adults face a twofold problem: First they are slower in detecting a perturbation to their system and second it is harder for them to initiate an adaptive response to a given perturbation. Both theoretical accounts imply a general lack of system robustness in the postural control of older adults that is associated with a higher vulnerability to perturbations to their system.

The age-related lack of system robustness, however, should not only result in an increased amount of processing fluctuations on the moment-to-moment level but also on longer time scales because perturbations can occur on different time scales. Older adults should be influenced more by these slow fluctuating perturbations than young adults. Thus, Hypothesis 2 predicted that the postural control performance of older adults should fluctuate more from trial to trial than the performance of young adults and Hypothesis 4 expected that older adults would show more processing fluctuations from day to day than young adults. The empirical investigation confirmed both hypotheses. Older adults showed more pronounced processing fluctuations in their postural control performance than young adults from trial to trial and from day to day. These findings are not trivial. In the cognitive domain, for example, the likelihood of significant age differences in trial-to-trial fluctuations is a function of task complexity. Roberts and Pallier (2001) failed to find reliable individual differences in young adults in measures of intraindividual fluctuations across a broad range of cognitive tasks. Their test battery contained rather simple cognitive tasks. In a related vein, West et al. (2002a) did not find significant age differences in processing fluctuations in simple-choice reaction time but in fluctuations in reaction time performances in a more demanding 1-back WM task. Bearing these results in mind, the significant age effects in processing fluctuations between trials and processing fluctuations between days speak for the high coordinative complexity at the level of subprocesses involved in the regulation of posture. The maintenance of the body's equilibrium is not a simple but a highly complex task that is practiced so often that it appears to be simple. The harmonic meshing of sensory, motoric, and cognitive processes necessary for efficient postural control is disturbed by senescent changes. This disturbance leads to an aging-associated increase in processing fluctuations on multiple time scales.

### 6.2.3 Interactions of Processing Fluctuations Across Time Scales

Processing fluctuations between trials or between days are in part causally related to the level of processing fluctuations at the shortest, moment-to-moment time scale. Moment-to-moment fluctuations were seen as elementary indicators of a general lack of system robustness, which also affect processing fluctuation on longer time scales. However, processing fluctuations at the more extended scales were assumed to be influenced by other additional factors fluctuating on their own respective time scales. The evaluation of whether age differences in trial-to-trial and day-to-day fluctuations contain information that is not captured by interindividual differences in moment-to-moment processing fluctuations is related to the problem of evaluating the adequacy of using the standard deviation as a unique source of information on age differences in cognitive reaction-time tasks. In the context of cognitive aging research, it is a common concern that age differences in intraindividual variability and more specifically processing fluctuations are a mere byproduct of age differences in average performances (e.g., Salthouse & Berish, 2005). In this respect, it was argued that for tasks that possess a lower boundary (e.g., reaction time has a minimum at zero), declines in the average performances move the distribution of potential performances away from that boundary. This movement should in turn increase the possibility for variation. A solution to this problem suggested by some researchers is to statistically control for interindividual differences in the average performance before age-related differences in measures of intraindividual variability are examined (e.g., Salthouse & Berish, 2005). In this dissertation, this suggestion was followed by introducing interindividual differences in moment-to-moment fluctuations (i.e., mean postural sway) as a covariate into the analyses of age differences in trial-to-trial or day-to-day processing fluctuations. It was found in these ANCOVA analyses that the age differences in trial-to-trial and day-to-day processing fluctuation were no longer statistically significant if interindividual differences in the average moment-to-moment fluctuations were taken into account. It has to be noted, however, that postural sway is not strictly a measure of mean performance, like mean RT, but is already a measure of variability on a short time scale.

#### *6.2.3.1 A Critique on the Between-Person Approach to the Distance-to-Boundary Problem*

From a methodological perspective there are a number of good reasons to doubt that the between-person statistical control of interindividual differences provides a good solution to the distance-to-boundary problem. These reasons are based on statistical considerations and have theoretical implications.

First, there might be a difference with regard to the relative reliability of measures of variability and central tendency. If the reliability of the mean is higher than the reliability of measures of variability then it could well be that the relationship between the average performance and age is stronger than the age relation of measures of processing fluctuations simply out of statistical ground. For example, in this study was the retest reliability (i.e., the correlation between performance indicators of the first and the second half of the study) .98 for the mean sway in simple standing and .97 for the mean sway in dual-task standing but the retest reliability of the amount of day-to-day fluctuations was .89 in simple standing and .86 in dual-task standing.

Second, empirical studies have shown that aging-related differences in performances are especially pronounced in the worst performances and not so much in the best performances, which is thought to be an indication of higher processing fluctuations in older adults than in young adults (e.g., Spieler et al., 1996). The worst performances, however, strongly influence the computation of the mean. Thus, paradoxically the greater the proportion of "bad" performances the more statistical control of the mean accounts for variance arising from processing fluctuations.

Third, thus far there are no general theoretical models that describe how average performance and intraindividual variability are functionally related (Rabbitt et al., 2001). Most analyses done in the field of cognitive aging simply assume a linear relationship between interindividual differences in means and interindividual differences in measures of intraindividual variability. It is, however, possible that the functional relationship between both performance indicators differs between the tasks under study and also between different individuals and age groups. Thus, there is a general concern that the relationship between measures of central tendency and variability might not be ergodic because sample homogeneity cannot be taken for granted (e.g., Molenaar, 2004).

The fourth concern addresses statistical problems associated with interpretability of between-person ANCOVA analyses. In the ANCOVA analyses applied in this dissertation the effect of moment-to-moment fluctuations was first partialed out as a covariate before the effect of age on trial-to-trial or day-to-day fluctuations was tested. These analyses were mathematically equivalent to a hierarchical regression analysis in which a unique effect of age group is evaluated after the control of a mediator variable. Lindenberger and Pötter (1998) highlight the risks of overinterpretation of mediator models by means of formal analysis and simulation. The most surprising result of their analyses showed that the unique effect of age critically depend on the squared partial correlation between the mediator variable and the dependent variable controlled for age. Therefore, the significance of the age effect on slow processing fluctuations in the ANCOVA analyses depends on the relation of the time scales that is orthogonal to age. Moreover, the control of interindividual differences in moment-to-moment fluctuations might reduce the effect of age on longer time scales even if processing fluctuations on multiple time scales are primarily attributable to independent processes. As a demonstration of the last statement, the case of the unique effect of age on trial-to-trial fluctuations in the simple standing condition is considered here. Age group membership was correlated with moment-to-moment fluctuations with a correlation coefficient of .54 and correlated with trial-to-trial processing fluctuations with a correlation coefficient of .53. If the partial correlation between both types of processing fluctuations is zero, the effect of age on processing fluctuations between trials after controlling for interindividual differences at the moment-to-moment level is still reduced by the spurious (i.e., completely mediated by age) interrelation between the different processing fluctuations. The spurious effect is given by the squared product of the two age correlations (e.g., Lindenberger & Pötter, 1998). In the example at hand, the spurious effect is $r^2_{spurious} = 0.082$ and the effect of age is $r^2_{age} = 0.28$. Therefore, controlling for interindividual differences in moment-to-moment fluctuations would have reduced the effect of age on fluctuations between trials by approximately 30% even if processing fluctuations on both time scales were functionally completely unrelated.

The statistical relations reported by Lindenberger and Pötter (1998) and the potential influence of spurious relationships illustrated in the example above cast serious doubts regarding the usefulness of a between-person control strategy to approach the distance-to-boundary problem. A number of issues associated with the between-person statistical control strategy of the distance-to-boundary problem, however, would not arise if the relationships between measures of central tendency and intraindividual variability were examined within single persons.

#### *6.2.3.2 Within-Person Control of Interdependencies Among Processing Fluctuations Across Multiple Time Scales*

Intraindividual relationships are relatively unbiased by spurious age-associated correlations. Within short time-intervals of data assessment, a within-person control strategy of the distance-to-boundary problem considers only the direct relationship between both performance measures because age is more or less a constant. Furthermore, in intraindividual analyses it is not necessary to assume that the relationship between measures of central tendency and intraindividual variability or the interrelationship of processing fluctuations on multiple time scales is the same for every individual.

With the data set used in this dissertation, it was possible to investigate at the within-person level whether age differences in trial-to-trial fluctuations (i.e., standard deviations across repeated trials) were completely a function of interindividual differences in moment-to-moment fluctuations (i.e., mean postural sway). Within-persons daily measures of trial-to-trial fluctuations were regressed on daily measures of moment-to-moment fluctuations. All within-person relationships thus obtained were positive, indicating that higher levels of moment-to-moment fluctuations were associated with stronger fluctuations between trials. A multi-level model found, however, significant interindividual differences in the strength of the relationship between the two measures of performance in simple standing and dual-task standing conditions. The homogeneity of within-person relationships is a necessary prerequisite for generalizations from between-person relationships to within-person processes (Molenaar, 2004; Lindenberger & Oertzen, 2006). Thus, it can be said that the relationship between the two types of processing fluctuations is not ergodic and a between-person control strategy inadequate. Furthermore, in both postural control conditions, the overall level of trial-to-trial processing fluctuations was strongly reduced by statistically controlling within-person fluctuations on the moment-to-moment scale but the age difference remained statistical significant (see Figure 15). In the between-person control analyses the same age difference in trial-to-trial fluctuations was no longer significant after controlling for interindividual differences in moment-to-moment sway. Consequently, it has to be assumed that a between-person control strategy is overly conservative and presumably partials out relevant age-related variance due to a spurious relationship. Unfortunately, it was not possible to analyze the relationship between day-to-day processing fluctuations and fluctuations on the moment-to-moment level within persons with the relatively simple approach reported here, because on the day-to-day level only between-person differences could be estimated. There is, however, *a priori* no good theoretical reason to believe that the interesting pattern found in the analyses of trial-to-trial fluctuations would not generalize to the even longer day-to-day scale.

### 6.2.4 Implications of Processing Fluctuations in Postural Control on Multiple Time Scales

A well functioning postural control system is a basic prerequisite for independent living in older ages (Brown & Woollacott, 1998). Moreover, there is a high incidence rate of falls in the elderly population (Lord et al., 1993). Falls in old age have a strong bearing on public health systems due to their direct and indirect, physical and psychological consequences on the elderly (e.g., Sattin, 1992). Therefore, the understanding of age-related changes in the postural control system and reliable diagnosis of older persons at risk of falling is of high public interest (Nevitt et al., 1989). Several authors have suggested that the direct assessment of the postural stability of older adults with force platforms could be used as a reliable diagnostic tool to discover potential balance problems in older adults (e.g., Woollacott, 2000).

The assessment of postural control performance with force platforms is, however, commonly done with a few trials on a single assessment session. In this dissertation, it is shown that older adults differ from young adults not only in their average amount of postural sway (i.e., moment-to-moment fluctuations), older adults are also more variable than young adults in their postural control performance from one trial to the next and from one day to the other. These findings have direct consequences with respect to the diagnostic value of single-session force platform measures of postural control in young and older adults. The assessment of postural control on a single session with a restricted number of trials is less reliable for older adults than for younger adults. Furthermore, it seems plausible that falls do not occur if the postural control system works with its average capacity but do in extreme situations when the system is vulnerable to perturbations. The amount of processing fluctuations on longer time scales may be a better indicator of how often the postural control system is in a vulnerable state than measures of average postural sway are. Further studies should evaluate whether processing fluctuations on long scales can predict falls in the elderly beyond the average postural sway (i.e., moment-to-moment fluctuations).

In a clinical diagnostic setting it is, however, unlikely that an individual client can be measured repeatedly because of the time and financial burden. Therefore, the question needs be addressed whether interindividual differences in postural sway (i.e., level of moment-to-moment fluctuations) measured on a single assessment can predict interindividual or age differences in trial-to-trial or day-to-day processing fluctuations. Results in this dissertation show that interindividual differences in average postural sway assessed at baseline predict age differences in trial-to-trial processing fluctuations but not age differences in day-to-day processing fluctuations. The age difference in day-to-day processing fluctuations could, however, be predicted by the level of postural sway averaged across 45 days of assessment. The same findings hold both for simple standing and dual-task standing conditions.

In summary, this thesis provided evidence suggesting that single-session performance assessments cannot account for the high level of day-to-day performance fluctuations of older adults. The reliability of single-session performance assessments is, however, influenced by performance fluctuations between days (see Ram et al., 2005). One implication that can be drawn from the empirical results of this dissertation is that instead of single-session assessments repeated measures across several days should be taken in order to improve the diagnostic validity of force platform assessments of postural control in older adults.

### 6.3 Sex Differences in Processing Fluctuations in Postural Control

Although the literature on sex differences in postural control is rather inconsistent (e.g., Kollegger, 1992; Wolfson et al., 1994), there seems to be a tendency that women display a lower level of moment-to-moment fluctuations in simple, unperturbed standing than men. Thus far, it is unclear whether this female advantage is due to higher-order systemic aspects of the postural control systems (e.g., better integration of sensory information) or due to beneficial anthropomorphic aspects of the female body (e.g., Golomer, 1997; Hageman et al., 1995). For example, some studies showed that sex differences disappear if interindividual differences in body height are statistically controlled. In contrast, a study by Golomer et al. (1997) showed a stronger reliance on visual information among men than among women. If the female advantage is based on higher system properties, it follows that women should have a more robust postural control system than men. Consequently, it was hypothesized that women would express lower levels of processing fluctuations than men not only on the moment-to-moment level (Hypothesis 4) but also on the trial-to-trial level (Hypothesis 5) and day-to-day level (Hypothesis 6).

In this dissertation, the empirical analyses showed that women swayed less than men from one moment to the next in the simple standing and dual-task standing experimental conditions. This effect of sex did not interact with age. However, at the trial or day level women - regardless of age group - did not show significantly lower levels of processing fluctuations than men.

Bearing the findings reported above in mind, it seems justified to argue that the female postural control advantage is not likely to be completely driven by a general higher level of system robustness among women than among men. Instead, the superior female postural control on the moment-to-moment time scale could be a consequence of static anthropomorphic sex differences. The average center of gravity is, for example, higher in men than in women because of the average height difference between the sexes. A lower center of gravity is easier to regulate than a higher one. In terms of dynamic systems theory, one can think of the adults' body height as a relatively fixed, time-invariant parameter in the dynamic systemic interaction that influences postural control. A low center of gravity may facilitate postural control regulation but may not increase the overall system robustness because it is fixed. Therefore, it may not increase the adaptivity of the system to perturbations.

### 6.4 Day-to-Day Couplings between Postural Control and Working Memory

In the sections above, the empirical results regarding age and sex differences in processing fluctuations in postural control on multiple time scales were reviewed and their theoretical implications were discussed. It was argued that age differences in processing fluctuations in the postural control system could result from senescent changes in the subsystems involved and also from age-related decline in dynamic interaction between subsystems. Consequently, processing fluctuations on different time scales may arise from a great variety of potential sources. An exhaustive examination of all potential sources or correlates of processing fluctuations in postural control on multiple time scales is beyond the scope of this dissertation work. Instead, the dissertation focuses on the examination of the potential role of processing fluctuations in attentional control in day-to-day processing fluctuations in postural control. Processing fluctuations in attentional control were operationalized by performance fluctuations in spatial n-back working memory for a number of reasons (see Section 4.4.2), particularly because working memory processes display strong age-related decline (e.g., Mayr & Kliegl, 1993; Mayr et al., 1996; Verhaeghen et al., 1997) and because age differences in processing fluctuations in n-back tasks have been demonstrated empirically (West et al., 2002a).

The influence of aging-related processes on the interaction of sensorimotor and cognitive performances has received considerable attention in recent years (see K. Z. H. Li & Lindenberger, 2002, Schäfer et al., in press, for review). It has been demonstrated in experiments that in dual-task situations concurrent sensorimotor and cognitive performances are more likely to interfere with each other in older adults than in younger adults (e.g., Huxhold et al., 2006). Furthermore, correlational analyses showed stronger between-person relationships between sensory/sensorimotor variables and cognitive variables in the elderly in contrast to the younger population (e.g., Anstey et al., 2003a, 2003b; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). Theoretical explanations of these findings have been suggested on different levels of analysis. The common cause account focuses on aging-related changes in a common third set of factors that has negative effects on sensory/sensorimotor performances as well as on cognitive performances (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). It has been proposed that senescent changes in the efficacy of dopaminergic neuromodulation and a resulting deficit in mental representations of the stimuli could be a candidate for such a common cause (c.f. K. Z. H. Li & Lindenberger, 2002; S.-C. Li et al., 2001). In comparison, the cognitive permeation hypothesis predicts that older adults have a higher need for cognition in sensorimotor performances than young adults (e.g., Krampe & Baltes, 2003; Lindenberger et al., 2000). In this perspective, older adults are more likely than young adults to use attentional control to compensate for their declining sensorimotor abilities (Lindenberger et al., 2000). The two perspectives, however, are not mutually exclusive. It is possible that both mechanisms are operating at the same time in the aging individual.

### 6.4.1 Why Study the Cross-Domain Couplings at the Level of Individuals?

It is clear that the common cause hypothesis and the cognitive permeation hypothesis focus on mechanisms at the level of individuals. In contrast, the empirical evidence, thus far, has been based on between-person correlational analyses and quasi-experimental contrasts of age groups in experimental designs. A generalization from between-person differences to intraindividual variation is formally legitimate only if one assumes variance equivalence and sample homogeneity (S.-C. Li & Schmiedek, 2002; Lindenberger & Oertzen, 2006; Molenaar, 2004). Variance equivalence requires the time invariance of variance-covariance structures. However, the phenomenon to be explained describes an age-related increase in covariation between sensorimotor and cognitive performances. Therefore, the first condition allowing a *a priori* generalization from interindividual to intraindividual variations is violated by definition. Given these considerations, this dissertation followed a person-centered methodological approach instead (Bergman et al., 2003; Molenaar, 2004). Moreover, the second formal condition, sample homogeneity, demands that intraindividual relations between variables are similar between persons. Therefore, it was an implicit task of this dissertation to empirically examine whether age-related differences in the strength of the covariation between sensorimotor and cognitive performances were equivalent across persons of a similar age.

### 6.4.2 The Study of Cross-Domain Couplings with Respect to Processing Fluctuations

Apart from methodological considerations regarding the issue of generalization from inter-individual differences to within-person mechanisms, there are also good theoretical reasons to study age differences in the interrelation between postural control and cognition on the level of processing fluctuations. This dissertation demonstrates that older adults express a higher level of processing fluctuations in postural control on multiple time scales than young adults. Although postural control is a highly practiced task that is usually performed without conscious attentional control, postural control can involve attentional mechanisms to some degree, for example, for the resolution of sensory conflicts (Teasdale & Simoneau, 2001). The cognitive permeation hypothesis would predict that older adults use attentional control to reduce the amount of processing fluctuations.

However, as has been outlined in the Theory section, older adults express higher levels of processing fluctuations in cognitive performances than younger adults, in particular in tasks strongly demanding executive functioning (see Hultsch & MacDonald, 2004, for review). In a seminal review article, MacDonald, Nyberg, and Bäckman (in press) conceptually integrated behavioral findings on interindividual differences of intraindividual variability in cognition with results from studies investigating potential neurophysiological substrates of processing fluctuations. The authors conclude that although levels of processing fluctuations in cognition are presumably linked to multiple neurophysiological underpinnings, increased levels of processing fluctuations are most strongly connected to dysfunctions in the prefrontal cortex. For example, a recent neuroimaging study demonstrated that processing fluctuations in cognitive performance at the behavioral level are correlated with fluctuating activation patterns in the prefrontal cortex (Braver et al., 2003). The prefrontal cortex in particular is subject to senescent changes (Raz et al., 2005). Recent neural-based models link the efficacy of attentional control to dopaminergic neuromodulation (e.g., Cohen et al., 2004). It has been demonstrated that carriers of an allele associated with high dopamine levels in the frontal cortex showed less intraindividual variability in a rapid perceptual comparison task than carriers of an allele associated with lower levels of dopamine (Egan et al., 2001). Thus, this study linked the level of dopamine activity in the frontal lobes to the amount of processing fluctuations in cognition. Several empirical studies as well as formal simulations suggest that aging-associated processes negatively affect the efficacy of the dopaminergic system, which in turn predicts negative aging-related changes in attentional control at the behavioral level (see Bäckman & Farde, 2005; S.-C. Li, Lindenberger et al., 2001, for reviews).

Therefore, older adults face a twofold dilemma. One the one hand, they are in a higher need of attention in postural control than young adults (Woollacott & Shumway-Cook, 2002). On the other hand, it has been shown that negative age differences in processing fluctuations are particularly pronounced in cognitive performances with strong executive or attentional control demand (e.g., West et al., 2002a). Such reciprocal influences between higher levels of processing fluctuations in postural control, postural control functions' greater reliance on cognitive processes, and more variable attentional control in later adulthood would probably contribute to increased couplings between cognitive and postural control processes.

#### *6.4.2.1 Intraindividual Cross-Domain Couplings*

This dissertation investigated intraindividual couplings between day-to-day processing fluctuations of postural control in a simple standing condition and spatial working memory performances assessed while participants were sitting. This particular analysis was chosen because it provides the opportunity for observing the relationship of fluctuations in working memory and postural control and working memory processes that is independent of possible trade-offs between the two tasks as in a dual-task situation. For instance, it has been shown that dual-task interferences could result in a performance decrease either in postural control or in cognitive performances and that the prioritization of tasks differs between individuals (e.g., Rapp et al., 2006). Potentially, task prioritization could also vary within individuals between days, which would make it difficult to demonstrate stable cross-domain couplings in dual-task settings.

Hypothesis 7 predicted that postural control demands attentional control to some degree and processing fluctuations in postural control should be positively correlated within persons to processing fluctuations in working memory. Therefore, in the context of this dissertation it was investigated whether a good spatial working memory performance on a given day is associated with good postural control performance on that same day. Postural control performance was measured in terms of COP area. Spatial working memory performance was operationalized in terms of reaction time[14]. Thus, a good day was indicated by negative deviances from the

[14] Accuracy was not considered as an outcome measure because analyses have shown that young adults did not show more than marginal levels of processing fluctuations in error rates.

intraindividual learning curve because fast reaction times and small COP areas indicate good performance. Analyses of multi-level models revealed that on average processing fluctuations in spatial working memory were significantly related to processing fluctuations in postural control. On average, a day on which reaction time performance was faster by 100 ms than predicted by the intraindividual learning curve the COP-area also decreased by about 5.75 $mm^2$.

However, as can be seen in Figures 20 and 21, the strength and even the direction of the intraindividual couplings between fluctuations in postural control and spatial working memory differed between individuals. Most surprisingly, positive and negative within-person cross-domain couplings were found in both age groups. Positive and zero within-person relationships can be explained by existent theories that primarily focus on attentional resource competition aspects (see Woollacott & Shumway-Cook, 2002, for review), whereas the obtained negative couplings cannot easily be explained from these perspectives. The next section introduces a conjecture based on a dual-process view of cognitive permeation of the interaction between cognition and postural control that can account for the full range of obtained within-person relationships.

### *6.4.2.2 A Dual-Process Model of Interindividual Differences in Cross-domain Couplings*

Theoretical approaches to dual-tasking postural control taking a resource allocation perspective focus on the beneficial effects of attentional control on postural regulation. As Huxhold et al. (2006) have demonstrated, however, directing attention to highly automatized postural control performance might actually decrease the efficacy of postural regulation depending on the situational context. The results of that study suggest a dual-process account of the relation between postural sway and cognition. In line with the constrained action hypothesis (Wulf et al., 2001), it is assumed that if the postural control task is simple, overt attentional control decreases postural performance by shifting the focus of attention on a highly automatized activity. If the postural control task is demanding, however, attentional control is needed for efficient postural regulation in line with the cognitive permeation hypothesis (Lindenberger et al., 2000).[15] The interaction between postural control and attentional control is, therefore, U-shaped. In experimental conditions in which participants are instructed to stand as still as possible one can assume that both processes operate across the full range of the U-shaped curve. Kahneman and Treisman (1984) argued that even highly automatized processes need a minimum of attentional

[15] The simplicity of the postural control task depends on the motoric and sensory task demands, external cognitive demands (e.g., dual-tasking vs. single tasking), and the amount of attentional resources of the individual (e.g., K.Z.H. Li & Lindenberger, 2002; Woollacott & Shumway-Cook, 2002).

resources. In the decreasing part of the U-function, the necessary amount of attentional resources is relatively small and the surplus of attentional resources is directed to highly automatized processes and harms postural control. With increasing cognitive demand more and more attentional resources must be invested in effective execution of postural control and less surplus can be directed at automatized processes, and consequently postural control improves. At a certain threshold the cognitive demand is higher than the available attentional resources and postural control decreases with increasing cognitive demand. The cognitive demand of a postural control task, however, has to be understood in relative rather than in absolute terms, because it is dependent on the resources of the individual (e.g., Huxhold et al., 2006). For example, as compared to younger adults, due to the senescent changes in their postural control system older adults will have a higher cognitive demand and an associated higher need for attentional resources even in simple standing than younger adults. These conclusions derived from dual-task experiments have strong implications for the interpretation of intraindividual cross-domain couplings.

The demonstration of processing fluctuations in postural control in this dissertation and processing fluctuations in working memory by other members of the Intra-Person Dynamics Group (see Schmiedek & Li, 2004) highlights that the amounts of attentional and sensorimotor resources are not constant within individuals. More specifically, if a participant has a good day in working memory, this indicates a high amount of attentional resources. However, the relative position of that individual on the U-shaped cross-domain interaction curve determines whether decreases in attentional resources on a given day will lead to an improvement or a decrement in postural control. With increasing cognitive demand of the postural control performance the effect of attentional control will gradually change from a detrimental influence to a beneficial influence on balance. The model predicts that with increasing average level of cognitive demand in the individual's postural control performance the intraindividual cross-domain coupling should become more positive. People with high functioning postural control are more likely to express negative correlations between fluctuations in working memory and postural control because for them high attentional resources imply that more attention is directed to highly automatized postural regulation processes. In contrast, people with low postural control efficiency should demonstrate positive cross-domain couplings because high attentional resources can support their deautomatized postural control systems.

It is, however, important to note that the model proposed here applies mainly to an experimental context in which the participants are instructed to minimize their body sway. In the real world, there are only rare occasions in which surplus attentional resources will be directed to automatized sensomotoric processes. In most daily situations, attention, which is not needed for an efficient postural regulation will be directed to other cognitive tasks (e.g., planning the day). However, there are some situations in which the detrimental effect of attention on efficient motor performance can be observed. For example, anyone who has tried to carry a tray full of glasses has experienced the urge to focus his or her attention completely on this task and may also have noticed that carrying becomes easier if not so much attention is paid to it.

### 6.4.3 Interindividual Differences in Cross-Domain Couplings

Following the suggestions by Baltes, Reese, and Nesselroade (1988) this dissertation employed a "bottom-up" approach to lifespan development (i.e., focused on single individuals before addressing interindividual differences). In these authors' perspective, development can be best characterized as multivariate patterns of change within individuals. Intraindividual patterns of change have to be described and explained before differences and commonalities between them can be addressed. In the extreme case, certain regularities arise only at the level of data aggregated across individuals (e.g., Estes, 1956). The power law of learning, for example, that has been dominating learning theories for a long time might be an artifact of data aggregation in the sense that sometimes not a single individual expresses a power function of learning but the aggregated curve does (Haider & French, 2002; Heathcote et al., 2000; Myung et al., 2000). Therefore, the basic units of analyses in this study were couplings between processing fluctuations in postural control and working memory at the level of single individuals. Only after the examination of the within-person cross-domain relations were the interindividual differences in within-person relations examined at the next level.

The common cause hypothesis and the cognitive permeation hypothesis predict that the interrelation between sensorimotor and cognitive functions increases in strength with advancing age (e.g., Baltes & Lindenberger, 1997; Krampe & Baltes, 2003; Lindenberger & Baltes, 1994). The dual-process model introduced in Section 6.4.2.2 further specifies the notion of cognitive permeation. The model predicts that with advancing age and an associated increase in the cognitive demands of postural control tasks intraindividual cross-domain couplings would become more positive. In Hypothesis 8, it was predicted that older adults would show higher intraindividual cross-domain couplings than younger adults. It was further predicted in Hypothesis 9 that women, because of their superior postural control performance in simple standing, would demonstrate lower intraindividual couplings than men. The effects of age group and sex were in the predicted directions. There was a tendency for older adults and men to show stronger within-person cross-domain couplings than young adults and women. Multi-level analyses, however, showed that neither age group, nor sex, nor their interaction could statistically differentiate interindividual differences in the strength and direction of intraindividual cross-domain couplings.

### 6.4.4 Interactions of Cross-Domain Coupling and Levels of Postural Control

Chronological age is not itself an agent of developmental changes but rather an accepted proxy for aging-related causal mechanisms (cf. S.-C. Li et al., 2004; S.-C. Li & Schmiedek, 2002). Common cause hypothesis and the cognitive permeation hypothesis attribute the strengthening of cross-domain interrelations to aging-related declines in cognitive and sensorimotor resources. In these perspectives, the level of attentional and sensorimotor resources is the underlying determinant of the strength of the cross-domain relation. In a related vein, predictions of sex differences in cross-domain within-person couplings were based on sex differences in the level of postural control performance.

However, age group, for example, predicted only about 29.5 % of the interindividual variance in the level of postural control indicated by the level of moment-to-moment fluctuations across days and only 52 % of the interindividual differences in the working memory reaction time averaged across days of assessment. Therefore, interindividual differences in levels of postural control and levels of working memory were used in multilevel models as direct predictors of cross-domain couplings at the interindividual level of analysis (i.e., the second level) to increase the statistical power.

The results of these multilevel analyses demonstrated that the lower the overall level of postural control the stronger and more positive the within-person relation between processing fluctuations in postural control and working memory. In contrast, neither the overall level of working memory nor the interaction of the level of postural control and level of working memory predicted significant variance in interindividual differences in cross-domain couplings.

The obtained findings add new insights into the existent theories regarding couplings of sensomotoric and cognitive performances because they allow theoretical predictions at the process level within individuals and also with respect to interindividual differences in within-person relations. In particular, it is interesting to note that the strength and direction of the intraindividual day-to-day couplings between postural control and spatial WM is more clearly driven by the status of the postural control system but not by the status of the cognitive system. This finding seems to be more in line with a cognitive permeation account than with a common cause account of the increased interdependence of sensorimotor and cognitive functioning associated with age, at least on the level of single individuals. The cognitive permeation view predicts that people with low postural regulation capacities use attentional control on “bad days” in terms of their postural control to compensate for their deficits. In a related manner, the dual-process model of the cognitive permeation hypothesis (Section 6.4.4.2) interprets the influence of interindividual differences in average postural control performance on the within-person cross-domain couplings as a gradual shift from negative to positive cross-domain relations. Here, the advantage of the dual-process model over the single-process model is that it can explain the full range of obtained within-person relationships. In contrast, from a common cause perspective, positive cross-domain couplings were assumed to be partly a result of day-to-day fluctuations in the efficacy of neuromodulation. Thus, positive couplings between sensorimotor and cognitive performances should have been associated with poor postural control as well as poor WM performance, because deficient neuromodulation is assumed to limit the performance in both domains of functioning (S.-C. Li, Lindenberger et al., 2001).

However, the negative influence of attention on automatic sensorimotor processes, the compensatory use of attention in postural control, and the potential influence of fluctuations in neuromodulation are not mutually exclusive mechanisms. From an integrative perspective, it is rather likely that all three mechanisms play a role in the complex interaction of sensorimotor and cognitive processes. For example, it can be reasoned that the influence of variability in prefrontal neuromodulation on postural control might only be evident in individuals with low balance performance, because their postural system is in particular need of prefrontal neuromodualtion to resolve stimulus ambiguities. It can be predicted that the relative influences of these mechanisms depend on the cognitive demand of the sensorimotor task. This demand is a function of the nominal task difficulty but also of the attentional and sensomotoric resources of the performer.

### 6.4.5 Why do Older Males Show Strong Cross-Domain Couplings?

In a follow-up multilevel analysis, it has been shown that the group of older men largely drove the interaction of interindividual differences in the level of postural control on the strength of within-person cross-domain couplings. The average strength of the intraindividual cross-domain couplings in the older men differed significantly from the average intraindividual coupling of the other participants. A deviance in working memory performance by 100 ms resulted in an average change of 0.94 $mm^2$ in postural sway in the group of young women, young men, and older women but in an average change in sway of 14.38 $mm^2$ in older men.

The group of older men was the age-by-sex group with the worst postural control performance. The dual-process model of cognitive permeation introduced in Section 6.4.2.2, implies that their postural control demands more cognitive resources than all other groups. As a consequence, the average cross-domain coupling should be highest in the older men, too.

Furthermore, a substantive explanation of the strong positive cross-domain couplings amongst older men could be that older men were in higher need of attentional control because their potential age-related deficit in sensorimotor performances interacted with the hypothesized stronger reliance of men on visual sensory information and an associated sensory integration deficit (Golomer, 1997; Teasdale & Simoneau, 2001).

## 6.5 Limitations and Outlook

In this section, problematic issues that arose in the context of this dissertation are discussed. In most cases, potential solutions to the reported problems stimulated ideas for future studies or the future use of new of statistical analysis techniques. Therefore, the dissertational limitations and outlooks are included in the same section. The first three sections refer primarily to methodological aspects of the data set used here, whereas the later two sections address more specifically conceptual issues.

### 6.5.1 Limitations in Sample Size

The main focus of the Intra-Person Dynamics Study was the accurate description of intraindividual variability and cross-domain couplings within individuals. In order to achieve this, the study design had a high density of repeated measurement occasions. Every participant was assessed in approximately 45 one-hour daily assessment sessions. For practical reasons, the intensive efforts involved in the assessment of a single individual worked against the inclusion of a large number of participants. After excluding some participants, each of the age groups contained 18 individuals. The consequence was that any between-person correlation within age groups would have to be based on 18 data points. The obtained data set is well suited for the investigation of within-person relationships but lacks power for between-person analyses. Therefore, this dissertation refrained from the use of between-person correlation not only for theoretical but also because of statistical reasons.

In the case of multilevel models, the particular data structure of the Intra-Person Dynamics Study has differential effects depending on the level of analyses. With 45 data points for each individual the first level parameters (i.e., the within-person level) can be accurately estimated, on average, and the estimation of the fixed effects can be assumed to be reliable (Hox, 1998; Maas & Hox, 2004b). However given only 18 persons per group, the accuracy of the standard errors of parameters of random effects at the second level (i.e., the between-person level) can be assumed to be relatively low (Hox, 1998; Maas & Hox, 2004a). The reliability of the cross-level interactions (i.e., the interactions between interindividual characteristics at the second-level and first-level relationships) is higher than the accuracy of random variances, but it is still less accurate than the estimation of fixed effects (Hox, 1998; Snijders & Bosker, 1999). Considering the costs associated with data sampling in nested designs, Hox (1998) advocates sampling at least 50 second-level units with 20 first-level units each as a rule of thumb if one is interested in cross-level interactions, and sampling at least 100 second level units with 10 level-one units each if the focus of examination is on random variances. Given that the design of the data set used in this dissertation contained only 36 second-level units (i.e., persons), it does not come as a surprise that the random variance in the cross-domain couplings did not reach significance although the visual inspection of the distribution of the within-person correlations showed marked interindividual differences.

In any study examining intraindividual relations a decision has to be taken to focus either on the accuracy of the estimation at an intraindividual level or at a between-person level because of the high costs involved and the time-intensive nature of assessment. Further studies on the within-person couplings between postural control and cognition should focus more strongly on interindividual differences. The number of persons should be increased in order to improve the power of significance tests of random variance parameters. To avoid an explosion of the associated costs the number of repeated measurements could be reduced or one could concentrate on intraindividual fluctuations on shorter time scales.

### 6.5.2 Counterbalancing between Single-Task and Dual-Task Conditions in Postural Control

In the design of the daily assessments the sequence of assessing simple standing (i.e., single-task performance) and dual-task standing conditions was counterbalanced by age and gender. A particular participant performed the two conditions always in the same order across all daily assessments. On the one hand, this approach had the benefit of allowing experimental analyses of the influences of age and gender on processing fluctuations that were not confounded by sequence effects. On the other hand, in the analysis of interindividual differences counter-balancing might bias results by introducing systematic between-person variance that is due to the experimental design. In this dissertation, interindividual difference analyses were restricted to the analysis of interindividual differences in intraindividual cross-domain couplings. Including the order of postural control conditions as an additional factor in the multi-level model analysis of between-person differences in intraindividual couplings revealed no relationship between the strength of the intraindividual cross-domain couplings and the order of assessing the postural control conditions.

### 6.5.3 Age-Related Differential Reliability of Cross-Domain Couplings

The empirical finding that older adults show stronger processing fluctuations from trial to trial than young adults has consequences regarding age contrasts of within-person couplings between processing fluctuations in postural control and working memory. The basis of cross-domain couplings was the mean postural sway (i.e., mean moment-to-moment fluctuations) on daily assessments. Trial-to-trial processing fluctuations were indicated by the standard deviation across the five trials that were assessed daily. Thus, older adults expressed higher standard deviations and therefore higher standard errors than young adults in the estimation of the average sway on a given day. As a consequence, the estimation of postural control performances on a given day was less reliable in older adults than in young adults. Furthermore, Schmiedek, Huxhold, Röcke, Li, and Lindenberger (2005) have demonstrated that the ratio of between-day variability to within-day variability in the spatial working memory task was lower in older adults than in young adults. Therefore, performance estimates in older adults were less reliable than estimates of younger adults in both dependent measures used in the examination of day-to-day cross-domain couplings resulting in less reliable estimates of couplings. In conclusion, processing fluctuations on a shorter time scale that are interesting phenomena in their own right, when the scientific attention is directed to this specific time scale, might function statistically as measurement error if phenomena in processing fluctuations on longer time scales are at the center of attention (Schmiedek et al., 2005).

Schmiedek et al. (2005) proposed that dynamic factor analysis may provide a solution to the age-related differential reliability in within-person bivariate couplings. Dynamic factor models have received increasing attention in multivariate behavioral research in recent years (Molenaar & Nesselroade, 2001; Nesselroade, McArdle, Aggen, & Meyers, 2002; Nesselroade & Molenaar, 1999). These models aim to identify multivariate covariance structures in intraindividual time series (e.g., Hamaker, Dolan, & Molenaar, 2005). Within-individuals a dynamic factor analysis can treat trials assessed within days as manifest performance indicators and model the day-to-day bivariate relationships at the latent level. Thus, the influence of the differential reliability in cross-domain couplings between age groups is reduced in dynamic factor analyses, given that bivariate couplings are examined at the latent level. In a following step, subpopulations showing a statistical similarity in their intraindividual covariance structure can be identified (Nesselroade & Molenaar, 1999). However, preliminary analyses of the data set at hand by means of dynamic factor analyses have shown that these models sometimes produced questionable parameter solutions (i.e., correlations greater than 1). Initial inspection of the problematic cases revealed that the likelihood of improper solutions was related to the reliability of the indicators forming the within-person factors. Future analyses of the intraindividual couplings between postural control and spatial working memory using dynamic factor analyses must either seek to improve the stability of the within-person factors by means of averaging or will need to try out different error structures (e.g., lagged error covariance structures).

### 6.5.4 Issues in Approximating the Degrees of Robustness of the Postural Control System

In this dissertation, processing fluctuations (i.e., variability in amplitudes of performances) have been used as indicators of processing robustness. Recent dynamic systems approaches, however, focus more strongly on certain conceptions of complexity of the output signal (i.e., variability in the frequency of change) as an indicator of processing robustness (e.g., Goldberger et al., 2002; Lipsitz, 2002). In these conceptions, healthy (i.e., robust) system performance is characterized by highly complex output patterns. Recent studies investigated the complexity of the signal by investigating the entropy (i.e., irregularity) or the amplitude of change in relation to the frequency of change in postural control within trials (i.e., Lipsitz, 2002; Thurner et al., 2002). For the sake of simplicity, the dynamic complexity of a given system has been equated with the irregularity of the output signal in the theoretical argumentations in this thesis, which is in line with a relatively long-standing tradition in dynamic systems perspectives of physiological systems (e.g., Lipsitz, 2002; Vaillancourt & Newell, 2002) Other conceptions of dynamic complexity stress the importance of regulatory feedback loops on multiple time scales that are associated with long-range (fractal) correlations in the physiological signal (e.g., Gilden, 2001; Goldberger et al., 2002). Long-range fractal behavior (i.e., self-similarity of the signal across time scales) is typically detected by an inverse power law (1/f) scaling pattern in the frequency spectrum (but see Wagenmakers et al., 2004, 2005, for a critical discussion). Future analyses of the data set at hand should consider the micro-dynamic aspects of postural control performances. The inclusion of these aspects opens a great variety of theoretically informative analyses because it considers a whole new wealth of information contained in the postural control performance assessment. As a hypothesis, it can be expected that senescent changes of older adults have resulted in a disruption of the long-range correlation patterns that are characteristic of high functionality. As a statistical approach, dynamic complexity could, for example, serve as a third level of analysis in multi-level models. At the first level of analysis, the dynamic pattern within trials could be estimated, which could in turn predict day-to-day performance fluctuations within individuals at the second level. At the third level, age differences in these relations could be examined. In a second set of analyses, it could be examined whether age-related disruptions in long-term scaling behavior are associated with higher cross-domain couplings.[16] Furthermore, it could be asked and examined empirically whether learning in postural control is associated with increasing long-range fractality in the postural control signal.

### 6.5.4 Process Specificity in Models of Sensorimotor and Cognitive Coupling

The conception of a general attentional resource sharing between sensorimotor and cognitive performances has resulted in valuable insights regarding the interdependence of both domains, particularly in the context of research on aging (e.g., Baltes & Lindenberger, 1997; K. Z. H. Li & Lindenberger, 2002; Lindenberger & Baltes, 1994; Lindenberger et al., 1998; Woollacott & Shumway-Cook, 2002). However, it can be criticized that such a conception of a general attentional resource is too broad and does not allow the identification of processes that link performances in both domains. In a related vein, researchers in the field of cognitive dual-task performance questioned a view of a general cognitive resource and suggested a different perspective (e.g., Navon, 1984).

#### *6.5.4.1 A Framework for the Dynamic Study of Cross-Domain Couplings and Interferences*

In a more differentiated perspective, the idea of a general resource structure or unit is replaced by a pool of distinguishable process resources that can be shared by two concurrent tasks in a dual-task situation, but not necessarily (Navon & Gover, 1979). The interference between two tasks that are performed concurrently depends on the degree to which specific resources are used by both tasks. This view may serve as a theoretical guideline to study cross-domain coupling at the process level. In the resource pool perspective, specific resources can differ in terms of the input dimension (e.g., visual or auditory), internal processing mode (e.g., spatial vs. verbal), response modes (e.g., manual or verbal), or cerebral structures underlying the internal processes (e.g., Friedman, Dafoe, Polson, & Glaskill, 1982). Research on the interference between postural control and cognition has already demonstrated that verbal responses interfere with postural control (Dault, Yardley, & Frank, 2003; Yardley, Gardner, Leadbetter, & Lavie, 1999) and that motor tasks share a greater resource overlap with postural control than cognitive tasks (Weeks, Forget, Mouchino, Gravel, & Bourbonnais, 2003). With respect to specific cognitive processes that cause the interference between cognitive processing and postural control it has been suggested that spatial processing interferes more strongly with postural regulation then verbal processing (e.g., Kerr et al., 1985; Maylor et al., 2001). However, the empirical evidence for such a

[16] However, as already mentioned in Section 6.5.1, the low between-person power limits the investigation of second level relationships.

relation is rather limited and ambiguous (see Huxhold et al., 2006). Future studies trying to disentangle specific processes need not only to explain the beneficial effects of attention on postural control but must also address the negative detrimental side of the coin.

#### *6.5.4.2 Processes Potentially Involved in Cross-Domain Couplings Between Postural Control and Cognition*

In this dissertation, attentional control was conceptualized within the framework of the unified theory of prefrontal cortex function that is based on recent neurobiological and neurocognitive approaches attempting to reveal the neuronal substrates underlying attentional control (see Duncan & Miller, 2002; Miller & Cohen, 2001, for review). In this model, attentional control is instantiated by the neuromodulatory influence exerted by the PFC on other brain areas involved in the specific task at hand. Such a conception of attentional control can be used to examine the U-shaped curve linking postural control and cognition.

As for the effect of direct attention on automatized processes of motor execution, in line with predictions from the constraint action hypothesis (Wulf et al., 2001), the findings by Huxhold et al. (2006) suggest that focusing attention on the execution of motor commands disrupts these processes and may result in a more cognitively controlled postural regulation. This claim is supported, in part, by recent neuropsychological evidence showing that directing attention to an overlearned finger movement sequence task increases the variability at the behavioral level (Rowe et al., 2002). Moreover, this increase in performance variability is paralleled by the finding that a stronger connectivity between the dorsal prefrontal cortex, an area involved in various selective attention tasks, and the premotor cortices was required when individuals were instructed to explicitly attend to their finger movements (Rowe et al., 2002; Stephan et al., 2002). In contrast, there is empirical evidence that attentional processes are specifically involved in sensory aspects of the postural control system. Behavioral data from dual-task experiments shows that the postural control system uses attentional control for sensory integration and selection between conflicting sensory information (e.g., Redfern, Jennings, Martin, & Furman, 2001; Teasdale & Simoneau, 2001). Therefore, attentional resource competition might specifically arise in dual-task situations because of the needs of the postural control system for attentional (i.e., prefrontal) modulation of sensory processing, on the one hand, and for the attentional control of the cognitive task on the other. The model of decreased neuromodulation predicts that older adults have less distinct mental representations than younger adults (S.-C. Li, et al., 2000). Moreover, according to the adaptive coding model (Duncan & Cohen, 2002; Cohen et al., 2004), a reduction in stimulus salience would lead to a stronger involvement of top-down modulatory control by the prefrontal cortex. Furthermore, there are empirical findings showing that older adults have specific deficits in automated processing of sensory stimuli (e.g., Alain, McDonald, Ostroff, & Schneider, 2004). The integration of the predictions of both models leads to the expectation that older adults are more in need to use controlled attention in postural control to compensate for these deficits than young adults are. Furthermore, older adults have deficient attentional control and stronger difficulties than younger adults to use it to improve their balance (Maki et al., 2001). This argumentation is supported by empirical evidence. For instance, it is highly cognitively demanding for older adults but not for young adults to reintegrate sensory information into their postural control system when it is made available to them after this information has been experimentally excluded (Teasdale & Simoneau, 2001).

*6.5.4.3 Age Differences in Sensorimotor-Cognitive Couplings: Key Features of Furture Research*

In sum, it can be speculated that the decreasing and the increasing parts of the U-shaped interaction between postural control and cognition might be governed by a differential influence of PFC modulatory activity. In the decreasing part of the function, PFC neuromodulatory influence could be directed primarily at motor aspects of postural regulation because the cognitive demand is low and not much modulatory enhancement is needed for cognitive processes. In contrast, with increasing cognitive demands, the need of the cognitive task execution conflicts with the need of the integration of the sensory aspects of balance for PFC-induced enhancement. Older adults are in greater need of attentional control of their sensory input than young adults. At the same time they have an age-related functional deficit in attentional control. Therefore, they demonstrate interference in dual-task situations at lower levels of nominal difficulty than young adults. Future studies should explore these considerations by varying independently and parametrically the sensory and cognitive demands of postural control. EEG recordings to obtain neuronal correlates of the observed postural control behavior should preferably accompany these experimental manipulations. In this context, recent neurophysiological studies demonstrated that detection of postural instability is accompanied by a burst in EEG gamma activity in the 30-50 Hz frequency band, primarily at frontal and prefrontal sites (Slobounov, Hallett, Stanhope, & Shibasaki, 2005; Slobounov, Tutwiler, Slobounova, Rearick, & Ray, 2000). The studies mentioned could not definitely differentiate whether bursts in gamma activity were indicative of sensory integration processes or preparatory processes related to movement initiation. In a future postural control study, it should be attempted to explore more precisely to which degree prefrontal gamma activity is coupled with oscillatory activity in sensory or motor areas and whether these couplings change with cognitive demand.

## 6.6 Conclusions

Lifespan psychology views adult development as being multidirectional, multidimensional, plastic, and contextualized (Baltes, 1987; Baltes, Lindenberger, & Staudinger, 2004). In this context, the developmental paths of individuals with their antecedents, correlates, and consequences constitute the theoretical foundations of scientific investigation (Baltes et al., 1988). In line with a perspective that highlights the intraindividual and multidimensional nature of developmental changes is the attempt to describe developmental trajectories with respect to their full scope (e.g., Nesselroade, 2004). Therefore, developmental research should not only characterize and explain stable aspects of behavior at a given point in time but should consider intraindividual variability and intraindividual covariation in these aspects at the same time. Lifespan psychology finally aims to understand developmental trajectories of intraindividual variance-covariance structures across levels and domains of psychological functioning in line with an understanding of commonalities and similarities in these developmental patterns between persons.

This dissertation contributed to the aforementioned endeavor by providing a thorough examination of age differences in processing fluctuations in postural control on multiple time scales. Due to senescent changes, the postural control system of aged adults is characterized by a low processing robustness resulting in maladaptive performance fluctuations across multiple time scales. To examine potential covariations of processing fluctuations in postural control a person-centered perspective was employed. Within-person relations across sensorimotor and cognitive domains were the basic units of analysis. In line with the predictions of the cognitive permeation hypothesis (Krampe & Baltes, 2003; Lindenberger et al., 2000), low sensorimotor functionality is associated with a strengthening in cross-domain couplings. Individuals of low postural control ability, in particular older men, demonstrate a positive within-person relation between day-to-day processing fluctuations in postural control and attentional control. This evidence suggests that these individuals use attentional control of their postural control performance to compensate for functional deficits in their postural control system. The intraindividual perspective provided valuable new insights into sensorimotor-cognitive couplings in a developmental context. Although the average tendency supported existent theories, within-person cross-domain relationships can differ markedly in terms of their strength and even direction. It has to be concluded that a generalization from between-person relationships to within-person processes of sensorimotor-cognitive couplings is not completely legitimate. Future theoretical models concerning the interrelation between sensorimotor and cognitive domains need to describe and explain between-person differences in within-person dynamics. It is hoped that the findings and conceptual considerations presented in this thesis represent first steps in this direction.