1. Introduction

For a long time, lifespan psychology has emphasized the individualized nature of human development (e.g., Baltes, 1987; Baltes, Reese, & Nesselroade, 1988). Before conclusions about similarities and interindividual differences in intraindividual trajectories can be drawn intraindividual change first has to be understood in terms of its antecedents, correlates, and consequences (c.f. Lindenberger & Oertzen, 2006). To gain a more thorough understanding about the full range of individual performances developmental research needs to consider more long-term aging-related changes as well as short-term intraindividual variability in behavior (e.g., Nesselroade, 1991). In this context, the assessment and analysis of intra-person variability has gained increasing momentum during recent years. In particular, processing fluctuations in cognitive performances that are defined as maladaptive intraindividual variations on relatively short time scales (e.g. trials, days, or weeks) have received remarkable attention in the last years (see Hultsch & McDonald, 2004, for review). In this dissertation, the conception of processing fluctuations is defined in a relatively broad manner. It is proposed that processing fluctuations are inherent features of any functional system that involves multiple subsystems, multiple control mechanisms, and interactions between the organism and the environment. Two theoretical perspectives hypothesize higher levels of processing fluctuations in older adults than in younger adults. The loss of complexity view ascribes high levels of processing fluctuations in older adults to senescent changes across a broad variety of interconnected subsystems leading to low levels of overall system robustness (e.g., Lipsitz, 2002). Recent neurocomputational models predict that older adults are more vulnerable to perturbations to their cognitive and sensorimotor systems than young adults (e.g., S.-C. Li Lindenberger, & Sikström, 2001).

Substantially, this dissertation focuses on age differences in processing fluctuations in postural control. In research on postural control, the level of postural control performance is commonly measured by processing fluctuations from one moment to the next. Age differences in processing fluctuations occurring on longer time scales (i.e., between trials or between days) have, however, not received much attention. This fact is surprising, given that the regulation of processing fluctuations is necessary to prevent falls, which are a common thread to older adults' mobility, independence, and health (e.g., Lord, Ward, Williams, & Anstey, 1993). Therefore, I will investigate age differences in processing fluctuations in postural control on three separable but interrelated time scales, namely, moment-to-moment, trial-to-trial, and day-to-day.

Furthermore, this dissertation seeks to identify a potential covariate of age differences in processing fluctuations in postural control. The common cause hypothesis and the cognitive permeation hypothesis (Lindenberger & Baltes, 1994; Lindenberger, Marsiske & Baltes, 2000), which are not mutually exclusive, both predict that sensorimotor and cognitive functions demonstrate an increasing cross-domain relationship with advancing age (see K. Z. H. Li & Lindenberger, 2002; Schäfer, Huxhold, & Lindenberger, in press, for review). Therefore, I will also examine as to whether day-to-day processing fluctuations in postural control are linked to day-to-day processing fluctuations in a cognitive task that puts high demands on attentional control.

Lifespan psychologists have repeatedly noted a divergence between theoretical models and empirical data that is used to support these models (Baltes et al., 1988; Molenaar, Huizenga, & Nesselroade, 2003). The empirical evidence regarding cross-domain correlations is primarily based on analyses of between-person variances that are used as substitutes for intraindividual variations. In contrast, the theoretical background explaining cross-domain associations is often based on intra-person mechanisms. A priori, this substitution is legitimate only under very rare formal conditions (Molenaar, 2004; Molenaar et al, 2003). In all other circumstances, the equivalence of conclusions based on the analysis of between-person differences and of conclusions based on the analysis of within-person variability is a matter of empirical inquiry (Lindenberger & Oertzen, 2006). Therefore, in this dissertation the relationships between processing fluctuations in the domains of cognition and sensorimotor performances are investigated on the within-person level.

The empirical inquiry is based on a sample of 18 young adults and 18 older adults who took part in the Intra-Person Dynamics Study (S.-C. Li, Lindenberger, & Smith, 2005). Sensorimotor and cognitive performances of these participants were assessed within one-hour daily sessions on approximately 45 consecutive weekdays. Analyses were conducted both (a) to investigate age differences in processing fluctuations from moment to moment, from trial to trial, and from day to day in postural control and (b) to examine age differences of within-person day-to-day couplings between postural control and spatial working memory. The empirical findings are embedded in the conceptual and methodological debate on studying sensorimotor and cognitive aging from a person-oriented, dynamic systems perspective (Nesselroade, 1991)

2. Theoretical Background

This dissertation seeks to investigate adult age differences in intraindividual variability in postural control. Nesselroade (1991) distinguished conceptually between intraindividual changes and intraindividual variability. In his terminology, intraindividual changes are defined as more or less enduring changes that are construed as developmental by virtue of the nature of their antecedents, their consequences, and their correlates (Baltes, 1987). Intraindividual variability, on the other hand, is defined as relatively short-term changes that are construed as more or less reversible and that occur more rapidly than intraindividual changes. A more detailed conceptualization of intraindividual variability has been included in the introductory sections of this dissertation, as well as an outline of how this conception has been integrated into recent research on adult aging-related differences in sensorimotor and cognitive functioning.

2.1 Concepts of Intraindividual Variability

The various theoretical approaches to the phenomena of intraindividual variability have different degrees of generality. In the following, the broad conceptualizations of intraindividual variability are illustrated, followed by a more specific discussion of the integration of concepts of intraindividual variability into a lifespan theoretical context. Different theoretically differentiable types of intraindividual variability will then be introduced in more detail.

2.1.1 Early and Recent Conceptualizations of Intraindividual Variability

As early as 1955, Fiske and Rice laid the foundations for a research program on intraindividual variability. In a review of a large body of studies, they argued that performance fluctuations are inherent features of complex biological organisms and that individuals from the same population may differ in the amount of performance variation they express. They concluded that it is possible to describe psychological functioning not only with respect to average performance but also with respect to fluctuations in performance. Fiske and Rice (1955) further suggested that three different types of intraindividual variability could be differentiated in terms of the sources they stem from. The first type refers to mere endogenous performance variations in which performance outcomes vary due to process variations within the organism in face of environmental stability. Examples for this type of variability are fluctuations in the response times of cognitive performances under constant experimental conditions. The second type of variability can be termed reactive variability and denotes the fluctuations in performances associated with the temporal order of events. This type of intraindividual variability is a consequence of the organism adjusting its performance in response either to an external stimulus it has recently reacted to or to a response to an external stimulus. This latter type of variability is exemplified prototypically in trial-and-error learning. The third type of intraindividual variation can be described as predominantly driven by external factors. It represents performance fluctuations primarily based on the adaptations of the organism to changes in the environmental context that is behaviorally relevant.

The threefold distinction proposed by Fiske and Rice (1955) is still theoretically appealing because it motivates detailed examinations of possible sources of performance variations within individuals. From the perspective of more recent conceptions, however, it is rather unlikely that these three different types of intraindividual variability occur in isolation.

More recently, the conception of humans as self-organizing living systems (e.g., Ford, 1987) has gained increasing attention and recognition as a metatheoretical framework within which issues regarding fluctuations in behavioral performance can be addressed. From this perspective, individuals can be understood as living systems consisting of hierarchically organized subsystems such as cells, tissues, and organs (Schroots & Yates, 1999). Furthermore, humans can be characterized as open, dynamic systems because human behavior consists of continuous interaction between environmental and internal factors. In this regard, human cognitive and sensorimotor systems are understood as complex, coupled ensembles of subsystems working together to achieve a variety of behavioral goals in the context of different task environments (Newell, 1998; van Gelder, 1998). According to this view, control over bodily and mental functions is achieved by a continuous, self-organized exchange of information and resources between subsystems and between the internal and external worlds. The dynamic interplay between the subsystems and their contexts gives rise to numerous variation patterns in performance across time. From a lifespan perspective, it is of particular interest to investigate how these variations patterns change in the course of life-long development.

2.1.2 Putting Intraindividual Variability into a Lifespan Perspective

Nesselroade (e.g., Baltes et al., 1988; Nesselroade, 1991; Nesselroade & Ram, 2004) has repeatedly emphasized the general importance of recognizing interindividual differences in intraindividual variability for a more complete understanding of lifespan development. He pointed out that even in human attributes that are assumed to show high relative stability at the mean-level (e.g., personality traits), fluctuations in performance within relatively short periods of time can be observed. Consequently, in order to characterize the individual’s status regarding a specific attribute at a given point in time, it is necessary to obtain a distribution of possible values and to estimate parameters that sufficiently describe this distribution. Accordingly, intraindividual variability is not seen as merely resulting from measurement error. In contrast, it is assumed that the level of intraindividual variability in a given psychological attribute is in itself a theoretically interesting source of interindividual differences. Moreover, developmental changes can manifest themselves not only on the level of average performances but also in the amount of intraindividual variability around these performances. In line with these considerations, it seems plausible to characterize aspects of behavior (i.e., the specific variables under study) with regard to their relative amount of intraindividual variability at a given point in time but also with regard to their developmental trajectory in intraindividual variations. Adopting this perspective, it becomes a question of empirical inquiry whether or not a specific human attribute is stable and trait-like or whether this attribute is highly variable and more state-like across the course of development (Nesselroade, 2004).

A comprehensive introduction to the full wealth of lifespan developmental psychology is beyond the scope of this dissertation. Baltes and colleagues (Baltes, 1987; Baltes, Lindenberger, & Staudinger, 2004) formulated and elaborated a number of key concepts of lifespan psychology. In the following, the discussion is restricted to the presentation to four key concepts of lifespan psychology, namely mutidirectionality, multidimensionality, plasticity, and contextualism, all of which are particularly pertinent in the context of research on intraindividual variability.

Multidirectionality refers to the fact that at any given developmental stage, age developmental trajectories cannot be completely generalized into a common functional growth or common functional decline factor. Childhood cannot be reduced to functional growth and old age not to functional decline. In both stages, gains and losses occur, although the ratio of these two differs between children and older adults. With respect to intraindividual variability, it has been documented, for example, that sensorimotor performances undergo multidirectional changes during childhood development, sometimes alternating between stages of high and low intraindividual variability (Thelen, 1995). Different directions of change in the magnitude of intraindividual variability within a given developmental stage should also be considered across domains of functioning. For example, there is some indication that the relative functional stability of emotional and cognitive domains differs in older adults (Röcke & Smith, 2004). Furthermore, the multidimensionality of developmental changes in intraindividual variability can also be observed within a functional domain at different levels (e.g., biological, information processing, and behavioral). It seems plausible that these different levels display a number of cross-level interactions that affect intraindividual variability at a given level of analysis (e.g., S.-C. Li, 2002). For example, S.-C. Li, Lindenberger et al. (2001) argued that senescent changes in neuromodulation (the biological level) are linked to more variable stimulus representations (the information processing level) and higher intraindividual cognitive performance variability (the behavior level).

One prominent question raised by lifespan psychology deals with the modifiability of behavior. This is reflected in the specific emphasis of lifespan psychology on the concept of plasticity. The conception of plasticity acknowledges the fact that there are many different realizations of developmental trajectories that are all constrained by the opportunity structure of a given individual during its development. Estimating the relative plasticity (or modifiability) of behavior for a specific person at a particular moment or developmental stage within a certain environmental context is one of the key notions of lifespan developmental research. Contextual factors can stem from a large number of sources. These sources can be, for example, cultural, societal, historical, or purely situational (e.g., performing in a group vs. performing alone). With regard to research on intraindividual variability, it is worth emphasizing that contextual factors and their influence on the observed behavior might change over time. Moreover, from a dynamic systems perspective, there is a constant interaction between within-person factors and contextual factors (Ford, 1987). In this vein, Nesselroade and Ram (2004) suggested conceptualizing intraindividual development as the full range of intraindividual variations in an ever-changing contextual environment.

In summary, given the ubiquity of intraindividual variability as an observable phenomenon, the investigation of intraindividual variability in cognitive and sensorimotor performances is valid in its own right as part of the research on the effects of aging on psychological processes (S.-C. Li & Lindenberger, 1999). A lifespan perspective can serve as a guideline in this endeavor. In particular, the notions of multidirectionality, multidimensionality, plasticity, and contextualism generate a framework within which the full scope of the phenomenon can be explored. A full integration of all four concepts into this dissertation is, however, not possible in a thesis of this size. Thus, issues regarding these four concepts in relation to intraindividual variability will be addressed to varying degrees in the course of this thesis. Moreover, the term intraindividual variability itself encompasses a variety of theoretically distinguishable phenomena. The next section provides a brief introduction to the different types of intraindividual variability.

2.1.3 Different Types of Intraindividual Variability

Building on the distinction between intraindividual change and intraindividual variability suggested by Nesselroade (1991), other authors have introduced further conceptual distinctions of subtypes of intraindividual dynamics (e.g., Allaire & Marsiske, 2005; MacDonald, Hultsch & Dixon, 2003; S.-C. Li, Huxhold, & Schmiedek, 2004; Lindenberger & Oertzen, 2006). Within a broader conceptualization of intraindividual variability, it is possible to categorize different subclasses of the phenomenon. These subclasses can be classified with respect to their time scale and the number of functional domains involved.

This differentiation with respect to time scales refers to the distinction between different levels of microgenetic variations and ontogenetic change. Microgenetic variations occur within short-term time scales (e.g., seconds, days, or weeks) and are relatively reversible. In contrast, ontogenetic change is relatively permanent and unfolds in response to cumulative and sometimes progressive influences over relatively long time spans (e.g., month or years). When classifying different types of intraindividual variability, a further distinction has to be made between variations in single functions and transformation of functional organization of more than one function. The examination of variations in single functions would implicate a univariate research strategy, whereas the examination of transformations in functional organizations would require a multivariate approach.

Variations in single functions and transformations in the functional organization of multiple functions take place within microgenetic as well as ontogenetic time scales and can be observed at different levels (e.g., the biological level, the information processing level, or the behavioral level). An example for the transformation in functional organizations within the microgenetic time scale is the task-dependent resource allocation in multi-task situations. For example, dual-task experiments indicate that if a situation is motorically challenging older adults invest cognitive resources into the control of sensorimotor performances (e.g., Krampe & Baltes, 2003; Lindenberger et al., 2000). The differentiation-dedifferentiation of ability structures across the lifespan is a good example of functional reorganization on an ontogenetic time scale. S.-C. Li, Lindenberger et al., (2004), for example, demonstrated that the factor structure of cognitive abilities is more compressed in older adults and children than in younger adults.

Variations in single functions within the ontogenetic time scale may result from, for example, processes of maturation and senescence at the physiological level but also by the processes of long-term learning and skill acquisition. The class of microgenetic variations in single functions has been conceptualized as consisting of a number of differentiable subtypes (e.g., S-C. Li, Huxhold, & Schmiedek, 2004; Lindenberger & Oertzen, 2006). Besides cyclic, rhythmic functional variations (e.g., circadian rhythms), microgenetic variations in single functions also embrace the concepts of plasticity, strategic diversity, adaptivity, and processing fluctuations. Figure 1 illustrates these different types of intraindividual variations.

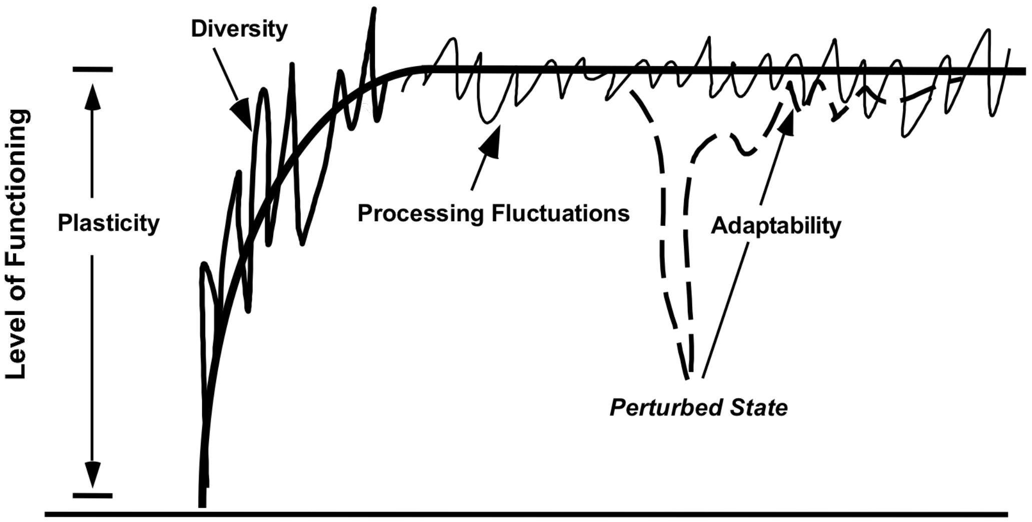

Figure 1. *Differentiating between Subtypes of Short-Term Intraindividual Variations. (Adapted from Li, Huxhold et al., 2004).*

Plasticity refers to short-term learning potential and can be indexed by the maximum training gain that a particular individual can achieve with short-term intensive learning. Strategic diversity is linked to exploratory behavior during the learning phase and is indicated by deviances from the learning curve that are positively correlated with the maximum performance. Adaptivity denotes the individual's ability to initiate appropriate responses that restore efficient functioning after being confronted with perturbations from inside or outside the organism. Processing fluctuations form the primary focus of this dissertation. Therefore, a more thorough definition of this term is given in the next section.

2.1.4 Processing Fluctuations

Many psychological and biological systems require dynamic interactions between multiple subsystems to achieve their functional goals. The term processing fluctuations is defined as the fluctuations around the maximum level of performance of an individual over relatively short periods of time. In general, processing fluctuations index the inability of a given system to reach consistently high levels of performance over short time periods. In psychological research articles, the terms processing fluctuations and lack of processing robustness are sometimes used interchangeably (e.g., S.-C. Li, Lindenberger, et al., 2004).

The concept of processing fluctuations is strongly related to the concept of system robustness as used in the biological sciences (e.g., Thomas, Lee, and Suh, 2004). System robustness refers to the ability of a system to produce desired outcomes in face of inherent noisy (i.e., stochastic) processes and under varying environmental constraints (e.g., Rao. Wolf, & Arkin, 2002). In theoretical biology, systems are considered robust if they are relatively insensitive to the precise values of the parameters (i.e., organismic and environmental constraints) under which they operate (Barkai & Leiber, 1997). According to this view, system robustness is functionally tightly linked to adaptivity. A functional system operates robustly if the process requirements at any given time-point are located within a range of potential values for which the system has been designed (Thomas et al., 2004). For example, stochastic enzymatic processes work efficiently only within a certain temperature range.

In summary, the robustness of a given biological system is commonly determined by how resilient it is to environmental changes and to random variations, including failures of its components (Dipple, Phelan, & McCabe, 2001). Similarly, processing fluctuations are expected to occur and can be observed behaviorally if short-termed disruptions from internal noisy processes or external perturbations drive the system away from its normal or maximum level of functioning. Thus, processing fluctuations are inherently maladaptive (S.-C. Li, Huxhold et al., 2004; Lindenberger & Oertzen, 2006). Processing fluctuations can be identified at the behavioral level by a negative correlation with either the maximum or standard level of performance (Allaire & Marsiske, 2005; S.-C. Li, Aggen, Nesselroade, & Baltes, 2001; S.-C. Li, Lindenberger et al., 2004).

Processing fluctuations have been conceptualized as a separate class of microgenetic variations. They are, however, related to other types of intraindividual variations. For example, although plasticity is regarded as a separate type of intraindividual variability, one might ask whether plasticity is present in the magnitude of processing fluctuations within a given developmental phase. For example, it is possible that different training regimes can either increase or decrease the amount of intraindividual fluctuations displayed. Furthermore, it is also likely that these hypothetical training effects vary between different age groups.

The definition of processing fluctuations distinguishes them from intraindividual changes in performance that are based on learning or long-term developmental changes as outlined above. It is, however, important to note that developmental changes have not been excluded from the conceptual considerations, design characteristics, and data analyses of the present dissertation. Rather adult age differences in processing fluctuations form the primary concern of this thesis.

2.2 Theoretical Accounts of Adult Age Differences in Processing Fluctuations

The next sections introduce two different theoretical perspectives that both consider processing fluctuations specifically in order to gain a better understanding of the processes associated with aging: the theory of complexity loss in aging (e.g., Goldberger, Peng, & Lipsitz, 2002) and the neural noise hypothesis of aging (e.g., Welford, 1981). The first approach arose primarily from the study of the influences of aging on motorical and autonomical physiological systems. The second approach, on the other hand, stems from research on cognitive aging. These two perspectives are then combined then in a summary section.

2.2.1 The Theory of Complexity Loss in Aging

A defining feature of many physiological systems is their apparent complexity. There are many definitions of complexity (e.g., Goldberger et al., 2002; Salthouse, 1992; Thomas et al., 2004;). In the context of dynamic system theories of aging complexity is most commonly defined in terms of information theory. Within such a perspective, the complexity of a system is determined by the number of parameters that must be known to predict the status of the system at a certain point in time. The complexity of physiological systems is rarely measured directly, but is often inferred from the irregularity (i.e., unpredictability) of its outcome signal across time.

In complex physiological systems, a vast variety of subsystems have to interact dynamically with feedback mechanisms operating on multiple time scales to produce a functional behavioral outcome (Goldberger et al., 2002). There have been recent attempts to model these features of physiological systems within the framework of dynamic systems theory. Some of these approaches assume that the output of healthy systems of high physiological complexity also reveals complex, variable patterns over time (Lipsitz, 1995). Lipsitz (2002) argued that these patterns are indicators of the individual's adaptive capacities within a given environment. Highly complex patterns indicate that the system under observation is more able to handle perturbations from within or outside of the system. In this respect, many authors find it useful to distinguish between the complexity of a behavioral signal and random fluctuation per se (e.g., Lipsitz, 2002; Slifkin & Newell, 1999). The complexity of a signal is related to the frequency of output change, which could, in principal, indicate adaptive readiness. Variability in the common sense, as for example quantified by the intraindividual standard deviation of performance, is more strongly linked to the amplitudes of changes in the performance over time. Higher amplitudes of non-systematic change are more likely to drive the system to its limits and thus could be seen to be dysfunctional in most cases (Lipsitz, 2002). The dynamic systems theory (see Beer, 2000; Van Gelder, 1998, for introduction) provides mathematical tools to model the time evolution of behavioral signals in the attempt to differentiate between these two types of variations and other types of system dynamics (but see Wagenmakers, Farrel, & Ratcliff, 2004, 2005). In the context of the loss of complexity hypothesis, these techniques have been repeatedly applied to study the influence of aging and disease on the time-evolution of behavioral signals (e.g., Lipsitz & Goldberger, 1992; Pincus & Goldberger, 1994).

Schroots and Yates (1999) suggested that if humans can be conceptualized as open, dynamic systems, the time course of their ontogeny would, then, follow the Second Law of Thermodynamics. This law states that there is an increase in disorder and dysfunctionality within a given system over time. Indeed, Lipsitz (2002) reviewed a number of studies indicating that older people experience losses in system complexity in many physiological subsystems, such as the cardiovascular system and the postural control system. Theoretically, these aging-associated losses could either result from a reduction of structural components or from less effective coupling functions between subsystems (Vaillancourt & Newell, 2002). It has been argued that those losses are associated with more regular, less complex patterns over time and higher amplitudes of performance fluctuations (i.e., processing fluctuations). These aging-associated developments in the time-evolution structures are assumed to cause higher vulnerability to perturbations in older adults (Lipsitz & Goldberger, 1992).[1]

The evidence for the conception of aging being generally associated with a loss of complexity in physiological signals is, however, still equivocal (e.g., Vaillancourt & Newell, 2002). There are several empirical examples showing aging-related increases of complexity that are correlated with higher levels of processing fluctuations in behavioral and physiological signals. Empirical examples include the domains of gait (Hausdorff et al., 1997), oscillatory force production (Vaillancourt & Newell, 2003), and hormone secretion (Pincus, Hartman, Roelfsema, Thorner, & Veldhuis, 1999). Vaillancourt and Newell (2002) argued that the effects of aging can manifest themselves either as a decrease or an increase in complexity depending on the specific task demands. They differentiated between tasks requiring a homeostatic control and tasks that require a homeodynamic control.

In homeostatic tasks, the system tries to avoid fluctuations to the greatest degree possible around a fixed equilibrium point (e.g., maintenance of the upright stand). This goal can be achieved in a more successful way by introducing multiple rhythms that dampen the influence of dominant, high amplitude rhythms. Successful task performance in homeostatic tasks is, therefore, associated with highly complex output patterns (e.g., Lipsitz, 2002). High complexity leads to small deviances from the equilibrium point (i.e., low variability in amplitude). It has been shown empirically that aging is associated with a decrease in complexity in homeostatic tasks.

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[1] To avoid any potential misunderstanding: This line of reasoning is not meant to imply that older people do not adapt to aging-related losses in bodily and psychological functioning. It only highlights that losses in processing resources are related to aging-related changes in the dynamics of behavioral and cognitive processing. Indeed, the way in which older people allocate their limited resources to different domains of functioning is an interesting topic in itself (see K.Z.H. Li, Lindenberger, Freund, & Baltes, 2001).

In homeodynamic tasks, the desired outcome varies systematically with time (e.g., sinusoidal functions of circadian rhythms). An optimal control strategy in these tasks varies the performance output as accurately as possible in correspondence with the required time function of the task demand. The introduction of multiple rhythms is assumed to lead, in the case of homeodynamic control, to deviances from the optimal performance function. Successful performance in homeodynamic tasks is characterized by output patterns of relatively low complexity, which ensures small deviations from optimal performance at a given time-point. There is also an accumulation of empirical evidence suggesting that older adults show higher complexity patterns in homeodynamic tasks than younger adults (see Vaillancourt & Newell, 2002, for review).

Based on considerations presented above, Vaillancourt and Newell (2002) postulated that structural losses in physiological systems associated with aging generally reduce the older systems capacities to successfully control their performance to meet environmental task demands. Depending on the nature of the task, this inability manifests itself either in decreased or increased signal complexity but generally leads to higher levels of processing fluctuations in older adults in contrast to younger adults.

Thaler (2002) commented on the conclusions drawn by Vaillancourt and Newell (2002). He alluded to the fact that successful control requires the successful perception of disturbances to the system. The smaller the deviance from the predefined “desired” criterion that can be detected, the faster the system can adapt to perturbations. He also made the assumption that deviances from the criterion point are less distinctive for older adults than for younger adults. Consequently, older adults are more likely than younger adults to react more infrequently and with higher amplitudes. Interestingly, this argumentation is very much in line with predictions arising from neural modeling accounts of processing fluctuations done in the domain of cognitive aging in the context of the neuronal noise hypothesis.

2.2.2 The Neural Noise Hypothesis

The neural noise hypothesis states that cognitive decline in aging is associated with a decrease in the signal-to-noise ratio in the central nervous system and was firstly formulated by Welford (e.g., Welford, 1981). Welford’s argumentation was primarily based on behavioral data on aging-related differences in cognitive performance. Vickers, Nettelbeck, and Wilson (1972), for example, measured the level of behavioral noise directly in a line-discrimination task that assessed objective perceptual differences. They found that older adults showed higher levels of noise in their performances than younger adults. Bruning, Holzbauer, and Kimberlin (1975) used signal detection theory to estimate the distinctiveness of mental representations that classified words as either learned or not learned. For older adults the two types of representations were less separable than for younger adults. The authors concluded that older adults were more disturbed by the effect of noise on the memory traces of words than younger adults.

Although Welford (1981) primarily cited behavioral studies to support his claim, his argumentation was already aimed at aging-related changes at the neuronal level. He postulated that a high level of neuronal noise in older adults is the consequence of an age-related decrease in the strength of the signals from the perceptual organs to the brain and between different brain regions relative to the level of random neural activity. Recently, attempts have been made to establish a framework for the integration of findings in cognitive aging-research across different levels of analysis, namely the biological, information processing, and behavioral level (e.g., Braver, et al., 2001; S.-C. Li, 2002; S.-C. Li, Lindenberger , 1999; S.-C. Li, Lindenberger et al., 2001). These approaches have particular importance for the study of processing fluctuations because they explicitly relate neural noise at the biological level to processing fluctuations at the behavioral level. In a cross-level framework, losses in the integrity of the central nervous system associated with aging and related decreases in catecholaminergic neurotransmitter modulation are assumed to lead to a noisier transmission of signals between neural circuits, which in turn has various behavioral consequences. In general terms, catecholaminergic neurotransmitters are assumed to amplify the strength of the neuronal signals to-be-processed in contrast to the level of random neural activity (e.g., Sawaguchi, Matsamura, & Kubota, 1988; Servan-Schreiber, Printz & Cohen, 1990). One neurotransmitter system suspected to be involved in a variety of aging-related changes is the dopaminergic system. Neurophysiological studies have shown a marked aging-related reduction in physiological markers of dopaminergic activity (see, Bäckman & Farde, 2004, for review). For example, the density of dopaminergic receptors in various brain regions including the prefrontal cortex displays a clear trend of aging-related decline (Kaasinen et al., 2000). Dopamine receptor losses in humans are associated with decreased performance on cognitive tasks requiring executive control, such as the Wisconsin card sorting test, digit span, or the Stroop task (see Arnsten, 1998; Kaasinen & Rinne, 2002, for review). A number of researches have investigated the correlative triad between aging, dopamine and cognitive function (see Bäckman & Farde, 2004; Bäckman, Nyberg, Lindenberger, Li, & Farde, in press, for review). Hierarchical regression analyses have shown, for example, that measures of dopaminergic receptor bindings could account for cross-sectional age differences in perceptual speed and episodic memory tasks. However, the effects of chronological age on these measures were significantly attenuated after controlling for interindividual differences in dopaminergic receptor bindings (Bäckman et al., 2000).

In summary, there is ample empirical evidence supporting the involvement of dopaminergic function in aging-related declines in cognitive performance. These empirical observations have stimulated theoretical discussions about the causes and the specific nature of the aging-related decline in cognitive performances (e.g., Braver et al., 2001; S.-C. Li & Lindenberger, 1999). Formal modeling approaches to the effect of aging on dopaminergic neuromodulation are particularly important with regard to research on processing fluctuations. For instance, S.-C. Li, Lindenberger, and Frensch (2000) modeled the functional effects of attenuated dopaminergic modulation associated with aging by systematically varying the gain parameter of a neural network model. The gain parameter determines a unit's reactivity to incoming signals. This approach mimics the general property of the dopaminergic system of regulating neuronal sensitivity to incoming signals by altering the sensitivity of postsynaptic neurons to afferent input (Sawaguchi et al., 1988). Furthermore, fluctuations in the release of neurotransmitters were simulated by randomly drawing different gain parameter values from a set of potential values at each processing step. The results showed that random fluctuations in the gain parameter caused greater output fluctuations at lower mean levels of the gain parameter than on higher mean levels. Moreover, intra-network variability subsequently altered the internal representations of stimuli. A lower gain parameter and consequently more variable network output caused less distinct internal representations of stimuli. Based on these computational results, S.-C. Li, Lindenberger et al., (2001) concluded that there is a potential link between aging-related losses in neuronal sensitivity, leading to a less distinctive internal representation of environmental cues and a more variable behavioral performance.[2]

The neural network modeling approach by S.-C. Li and colleagues (S.-C. Li et al., 2000; S.-C. Li, Lindenberger, et al., 2001) suggests that decreased neuromodulatory efficiency associated with aging might amplify random neural activity and consequently lead to a less desirable signal-to-noise ratio in older adults than in younger adults. Lower signal to noise ratios cause higher levels of processing fluctuations at the behavioral level than higher ratios. From this perspective, it becomes clear that older adults can be expected to differ from young adults not only in their average cognitive performance but also in the amount of cognitive processing fluctuations.

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[2] The implications of the neural modeling work done Li and colleagues for cognitive aging research with regard to theorizing and guidance of empirical questions are manifold (see, S.-C. Li, 2002). In the context of this dissertation, however, an elaboration of these implications will be restricted to those relevant for the conceptualization of aging-related differences in processing fluctuations.

2.2.3 Integrating the Perspectives of Complexity Loss and Neural Noise

Interestingly, the model formalizing the influence of dopaminergic neuromodulation in cognitive aging complements the dynamic perspectives about the loss of physiologic complexity associated with aging. To give a brief recapitulation, the loss of complexity hypothesis states that many physiological systems, including neuronal systems, experience structural losses of system components and decreased efficiency of coupling functions between subsystems. Both of these processes lead to a reduced capacity of aged systems to successfully apply controlling schemes to reduce undesired performance fluctuations (Vaillancourt & Newell, 2002). In line with this perspective, structural and functional losses in the dopaminergic neuromodularatory system (e.g., losses of neurons, receptors, efficacy of receptor bindings etc.) decrease the efficiency of successful discrimination between signals. The increased signal-to-noise ratio associated with the aforementioned structural losses presumably hampers the transmission of signals between cortical circuitries that are in need of modulatory control. In terms of dynamic systems theory, the increased signal-to-noise ratio indexes negative alterations in the coupling functions between systems. Thus, the model of decreased dopaminergic neuromodulation associated with aging resembles a special case of the loss of physiological complexity theory. The great advantage of the decreased neuromodualtion model is that it specifies a concrete neuronal mechanism and posits a major source of processing fluctuations as originating from neuronal information processing with low fidelity.

Furthermore, the observation of less distinctive stimulus representation in “aged” neural networks reported by S.-C. Li and colleagues (e.g., S.-C. Li et al., 2001) is in line with the theoretical predictions by Thaler (2002). Thaler (2002) proposed that the inappropriateness of systemic control observed in older people in comparison with younger people (see, Vaillancout & Newell, 2002, for review) might be caused by the inability of older systems to detect small differences between the desired and the actual state of the system. If cortical representations are less different from each other in older adults than in younger adults, it seems highly plausible to assume that the necessary feedback mechanisms for systemic control also display lower functionality with advancing adult development. Consequently, it can be expected that young adults are able to react to smaller deviances from the systems’ criterion settings than older adults. Thus, across time, older adults will show greater amounts of processing fluctuations at the behavioral level than younger adults.

2.3 Aging and Processing Fluctuations in Cognition

In the cognitive aging literature, intraindividual fluctuations are often parameterized with regard to the standard deviation of trial-to-trial reaction time fluctuations, which some researches also term inconsistency (e.g., Hultsch & MacDonald, 2004). In this dissertation, the term processing fluctuations is preferred because it does not only refer to intrapersonal behavioral variability but also to its maladaptive nature (see Section 1.1.4; S.-C. Li, Huxhold, et al., 2004).

The following section reviews extant evidence on aging-related differences in processing fluctuations in cognitive performance. First, it is shown that empirical studies have established measures of processing fluctuations in cognition as reliable indicators of interindividual differences. Second, it is highlighted that increases in processing fluctuations with age are commonly observed in adulthood and old age. Moreover, some empirical studies imply that the level of processing fluctuations might be especially informative about the status of the aged cognitive system. Third, empirical evidence is reported to demonstrate that aging-related differences are particularly pronounced in tasks that place high demands on executive processing.

In order to show that processing fluctuations in cognitive performance have validity in its own right in the context of research on cognition and cognitive aging, two necessary conditions must be met. First, it must be demonstrated that processing fluctuations can be reliably measured. Second, it is necessary to make clear that processing fluctuations allow insights into cognitive phenomena that cannot be gathered by the investigation of average performance.

2.3.1 Processing Fluctuations: Reliable and Unique Measures of Cognitive Functioning

The amount of variability in the execution of a given cognitive task is an important and stable characteristic of the person (e.g., Jensen, 1992; Rabbitt, Osman, Moore, & Stollery, 2001). For instance, an early study showed that processing fluctuations measured as trial-by-trial response-time variability successfully discriminated between patients showing mental deficiencies and a control group (Berkson & Baumeister, 1967). In a similar vein, Hultsch, MacDonald, Hunter, Levy-Benchton, and Strauss (2000) demonstrated that processing fluctuations measured as standard deviations in reaction time performance indicated reduced levels of neurological functioning (i.e., a diagnosis of mild dementia) even when differences in average performance were taken into account. Furthermore, Carron and Bailey (1969) showed that measures of processing fluctuations showed high between-person reliability across days. Jensen (1992) reported significant odd-even reliability estimates for trial-to-trial processing fluctuations in reaction times. The odd-even reliabilities of processing fluctuations were, however, of lower magnitude than the odd-even reliabilities of measures of central tendency. All authors mentioned above concluded that intraindividual fluctuations do not simply occur due to measurement error but rather represent a robust phenomenon in which reliable individual differences can be found.

Average performance measures and measures of processing fluctuations are empirically correlated (e.g., Hultsch & MacDonald, 2004; Jensen, 1992; S.-C. Li et al., 2001; Salthouse & Berish, 2004). For example, longer average reaction times are accompanied by greater trial-by-trial standard deviations. Therefore, attempts have been made to validate the assertion that measures of processing fluctuations contain information that is not captured in measures of average performance.[3] In this regard, Ram, Rabbitt, Stollery, and Nesselroade (2005) investigated the multivariate structure of mean performances and processing fluctuations in six different conditions of a letter recognition task using a chain P-factor technique. A chain P-factor analysis was used to integrate information concerning between-person differences with information gathered by within-person repeated measurements. Participants included in the analyses were measured repeatedly over 36 weeks. Nested hierarchical modeling analysis revealed that two latent factors, one comprising interindividual differences in mean performances and the other composed of interindividual differences in processing fluctuations, provided a better model fit for the data than a single factor solution. Thus, it can be concluded that measures of processing fluctuations and measures of central tendency provide distinct sources of information about interindividual differences in cognitive functioning. Moreover, interindividual differences in processing fluctuations convey information about the overall status of the cognitive system that go beyond information entailed in interindividual differences in average cognitive performances. For example, in a review of seven studies, Jensen (1992) showed that interindividual differences in trial-by-trial variability in reaction time performance predicted psychometric intelligence better than the individual's median RT. Rabbitt et al. (2001) found that people who scored highly on a culture-fair intelligence test displayed lower amounts of processing fluctuations than people with low intelligence scores.

2.3.2 Aging is Associated with Increased Processing Fluctuations

In recent years, a number of studies have examined the validity of performance fluctuations empirically in order to increase our understanding of aging effects in the domain of cognitive functioning. Older adults showed higher performance fluctuations in cognitive performance than younger adults across a variety of different tasks. Aging-related differences in the amount of processing fluctuations in cognitive performances have been observed in simple reaction time

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[3] From a theoretical point of view, it might make sense to focus on processing fluctuations even if their correlation to average performance is strong because processing fluctuations could be a more direct expression of the key features of the theoretical model.

and choice reaction-time tasks (e.g., Bunce, MacDonald, and Hultsch, 2004; Hultsch, MacDonald, and Dixon, 2002), time-estimation tasks (e.g., Wearden, Wearden, & Rabbitt, 1997), semantic and lexical decision tasks (Hultsch et al., 2002), working memory tasks (West, Murphy, Armilio, Craik, & Stuss, 2002), and inhibition tasks (e.g., West, 1999). For example, Hultsch et al. (2002) investigated aging-related differences in intraindividual fluctuations between a sample of young adults (17-36 years) and a sample of older adults (54-94 years). The participants performed multiple trials on a non-verbal simple reaction-time task and choice reaction-time task, a lexical-decision task, and a semantic-decision task. Significant aging-related differences in within-person performance fluctuations were found, even after aging-related differences in the speed of performance were statistically controlled. Furthermore, it is of particular interest that aging-related differences in cognition exist sometimes exclusively at the level of processing fluctuations. Wearden et al. (1997), for instance, found that aging-related differences in a time-estimation task were absent in the mean performance but could be observed in measures of intraindividual fluctuations. Such a finding points to the fact that if processing fluctuations in performance are ignored, some aspects of differences between young and older adults in their respective cognitive systems might go unnoticed. Furthermore, in line with the theoretical predictions from the neural noise theory of aging, there is some indication that processing fluctuations are specifically informative about the status of the cognitive system of older adults (e.g., Bunce et al., 2004; Hultsch, et al., 2002; S.-C. Li, Lindenberger et al., 2004; MacDonald, Hultsch, & Dixon, 2003).

2.3.3 Processing Fluctuations as Indicators of the Status of the Aged Cognitive System

The model of decreased neuromodulation suggests that increased processing fluctuations across various tasks may be expressions of a common mechanism that changes with aging. More specifically, decreased neuromodulation may lead to lower signal-to-noise ratio of neural information processing, which, in turn, could result in greater processing variability (Li et al., 2002). Therefore, processing fluctuations in cognitive performance might measure more directly aging-related differences that are primarily caused by a lowered signal-to-noise ratio than measures of average performances. Information gained by investigating processing fluctuations might contribute to the discovery of the driving forces behind aging-related changes.

Bunce et al. (2004), for example, showed that aging-related differences in processing fluctuations in choice reaction time tasks are driven by fluctuations in the decision processes and only to a lesser degree by sensorimotor aspects of the tasks. This finding supports the neuromodulation view by suggesting that aging-related differences in cognitive processing fluctuations stem more strongly from central processing deficiencies rather than arising from peripheral processes. Consistent with this proposition, Hultsch et al. (2002) found that processing fluctuations were more widely correlated with measures of perceptual speed, working memory, episodic memory, and crystallized intelligence in older adults than in young adults. Similarly, a recent study found that processing fluctuations in reaction time were more strongly correlated with measures of fluid intelligence in older adults than in younger adults (S.-C. Li, Lindenberger, et al., 2004). Moreover, processing fluctuations do not only provide information about the current status of cognitive functioning, but are also capable of predicting the extent of longitudinal, aging-related decline in cognitive performance. Longitudinal analyses showed that high levels of processing fluctuations in reaction time performance at baseline assessment predicted aging-related declines in perceptual speed, working memory, and episodic memory in a sample of older adults (54-89 years) over a 6-year period (MacDonald et al., 2003). Taken together, both cross-sectional and longitudinal correlational evidence indicates that aging-related changes in processing fluctuations in reaction time tasks and performance decrements in higher order cognitive functions might be driven in part by the same ensemble of causes.

2.3.4 Processing Fluctuations in Executive Functions (Attentional Control)

Despite the fact that aging-related differences in processing fluctuations have been found across a variety of different tasks, the question has still been raised as to whether there are cognitive processes that are more likely to express aging-related increases in processing fluctuations. In this respect, processes involving high degrees of executive control or attentional control have been suspected to be specifically susceptible to processing fluctuations.

Executive control is instantiated by the cognitive functions that select, program, and coordinate the computational processes required for perception, memory, and action (Cepeda, Kramer, & Gonzalez de Sather, 2001). Depending on the theoretical perspective taken, executive functioning is often equated with attentional control or attentional controlled processing. In the course of this thesis, the terms executive functioning and attentional control are used interchangeably. According to Smith and Jonides (1999), executive control processes can be classified into a number of separable but interrelated cognitive functions. Three often postulated executive functions are mental set shifting, information updating and monitoring, and inhibition of task irrelevant processes. The first executive function, mental set shifting, is often also called “attention switching” or “task switching”. It refers to the ability to shift back and forth between multiple tasks, operations or mental sets. Updating and monitoring denotes all of the processes that are responsible for coding task-relevant incoming information, consecutively adjusting items held in working memory, and releasing information that has become irrelevant from online memory storage. Inhibition of task irrelevant processes describes the ability to overcome interference that would otherwise disrupt task performance. Using confirmatory factor analysis, Miyake, Friedman, Emerson, Witzki, and Howerter, (2000) demonstrated that the executive functions mentioned above can actually be understood as separable but interrelated functions presumably sharing some common mechanism.

Recent neurobiological and neurocognitive approaches attempt to reveal the neuronal substrates underlying executive functions or attentional control (see Duncan & Miller, 2002; Miller & Cohen, 2001, for review). These recent proposals differ from common neurocognitive approaches in that they are not specifically aimed at dissociating particular brain regions involved in certain aspects of attentional control but rather try to understand the phenomenon at a systems level (Cohen, Aston-Jones, & Gilzenrat, 2004). In this respect, executive control or attentional control is defined as the online modulation of attentional and response processes by maintaining information about the context (e.g., Cohen et al., 2004; Cohen, Botvinivk, & Carter, 2000). The general idea of a systems-level of attentional control has been integrated into a unified theory of prefrontal cortex function (Duncan & Miller, 2002; Miller & Cohen, 2001). According to this view, attentional control emerges from the orchestrated interplay of a number of brain regions in which the prefrontal cortex (PFC) plays a pivotal role (Miller, 2000). It has been found that neurons in the PFC are substantially reactive and adaptive in correspondence to behavioral task demands or, in other words, the context in which the behavior occurs (see Duncan & Miller, 2002, for review). These prefrontal cortex representations of context information exert top-down control by providing excitatory signals that bias processing in other brain areas towards task-relevant information (e.g., Miller, Erikson, & Desimone, 1996; Cohen et al., 2004). Biased processing may either arise from the excitation of neurons coding task-relevant information or from the inhibition of neurons coding task-irrelevant information. Depending on the specific brain area to be addressed by top-down control, the PFC can be involved in the selection of specific sensory inputs (i.e., attentional processes), memories (i.e., retrieval processes), or motor outputs (i.e., motor response selection) (Miller, 2000).

The predictions that the model allows to make are of great importance for the investigation of aging-related differences in cognition. According to one model, the strength and the accuracy of the mental representation in the PFC largely depend on dopaminergic neuromodulation (e.g. Braver et al., 2001; Cohen et al., 2004). As already mentioned, the dopaminergic neurotransmitter system shows a tremendous aging-related decline, which is especially pronounced in the PFC (Kaasinen et al., 2000). In behavioral terms, it might be possible to show that older adults are disproportionately impaired in contrast to younger adults in tasks that strongly require the active maintenance of context information (Braver et al., 2001), multiple task settings (Verhaeghen & Cerella, 2001), or global transformations in working memory (Mayr &

Kliegl, 1993). All of these cognitive processes are assumed to strongly rely on executive functions.

2.3.4.1 Processing Fluctuations in Executive Control: Empirical Evidence

One important but less studied aspect of executive control functions is that they seem to fluctuate in efficacy over time, leading to periods of optimal and non-optimal performance (Braver, Reynolds, & Donaldson, 2003; West, 2001). A classical study (Bills, 1931) demonstrated that during continuous cognitive performance mental blocks of briefly disrupted processing efficacy occur occasionally. These blocks are indicated by very slow reaction times that lie well outside the person-specific normal range of reaction times. Broadbent (1953) interpreted such mental blocks as evidence for involuntary shifts of attention to irrelevant sources. Bunce, Warr, and Chochrane (1993) linked this explanation to the principles of inhibitory mechanisms. In their interpretation, disruptions of processing efficacy were likely to be caused by the intrusion of task-irrelevant information into the stream of thought. Thus, mental blocks could indicate temporary failures of one of the primary executive control functions, namely the inhibition of task irrelevant processes. This rationale is supported by a number of empirical findings.

Using a task-switching paradigm, Segalowitz, Poulsen, and Segalowitz (1999), for example, showed that increases in mean RT were only paralleled by increases in the coefficient of variation[4] if the task required executive control. Further relevant evidence was obtained by characterizing individual response-time distributions for a given cognitive task more completely with ex-Gaussian functions. Ex- Gaussian functions approximate the individual's often positively skewed latency distribution with the convolution of an exponential and a normal (Gaussian) distribution in a three-parameter model. The parameter μ and σ denote the mean and standard deviation of the Gaussian part of the distribution, while τ reflects the mean and standard deviation of the exponential component. Thus, τ gives an estimate of the tail of the response time distribution. Spieler, Faust, and Balota (1996) fitted an ex-Gaussian function to reaction time distributions derived from a Stroop task. The Stroop effect is the name for the increase in reaction time that occurs when participants have to name the color of the ink in which a color name is printed and the word meaning differs from the ink color (incongruent condition) as compared to when it does not differ (congruent condition). Performance on the Stroop task is assumed to rely on the individuals' ability to successfully inhibit the tendency to respond to the word meaning. The ex-Gaussian analyses applied by Spieler et al. (1996) revealed that, for young

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[4] The coefficient of variation is the person-specific standard deviation divided by the mean or median of the individual's distribution of reaction times, thus indicating the level of within-person variability that is independent of the central tendency.

adults, the interference effect of the incongruent condition was only expressed in the τ parameter. One interpretation for the increased tail of the distribution is that lapses in attention occasionally occur during sustained processing. In a number of trials, participants involuntary devote more processing effort to the word meaning than is typically the case, which indicates fluctuating executive control processes.

2.3.4.2 Higher Fluctuations in Executive Control in Older Adults

West (2001) proposed that the decreased efficacy of executive control processes in older ages leads not only to mean differences in young-old comparisons but that fluctuations in executive control are also more pronounced in older adults than in younger adults. The occasional failures of attention or of a given mental set to guide behavior successfully are termed lapses of intention. Lapses of intention are much more frequent in older adults than in young adults (West, 1999a). Based on this observation, West (1999a) concluded that executive control processes operate at suboptimal levels more frequently in older people than in younger people. Ex-Gaussian analyses of reaction time data revealed that differences in performances between age groups are likely to be found in the τ parameter indicating prolonged processing times on a larger number of trials in older adults than in younger adults. For example, Spieler et al. (1996) found that the magnitude of the Stroop-effect was equivalent for a young and an old group on the μ parameter (i.e., the mean of the Gaussian part of the distribution) whereas the age difference in the τ parameter was significant. Using also ex-Gaussian analyses, West (1999b) contrasted two versions of an n-back working memory task. In n-back tasks, a series of items is presented at a constant presentation rate. In the 0-back versions of the task, a response that is made with respect to an item follows immediately after presentation. In the 1-back conditions, participants have to respond to the item one position back in the sequence. Thus, the 1-back conditions demand executive control with respect to monitoring and updating items held in working memory. In his analysis, West (1999b) found that experimental effects contrasting 0-back and 1-back conditions were expressed only in the τ parameter for younger adults. Although older adults showed effects of executive control demand in the μ parameter, aging-related differences were particularly strong in the τ parameter. In a follow up study, West, Murphy, Armilio, Craik, and Stuss (2002) demonstrated that aging-related differences in intraindividual fluctuations were restricted to tasks demanding executive control. West et al. (2002) concluded that, compared to younger adults, older adults are particularly susceptible to fluctuations in the efficacy of executive control processes.

Braver, Reynolds, & Donaldson (2003) found that fluctuations in the activations of specific areas in the PFC were predictive of trial-to-trial processing fluctuations in a cognitive task strongly demanding executive control (i.e., task switching). According to the unified theory of PFC functioning mentioned before, activations in the PFC depend strongly on dopaminergic neuromodulation (Duncan & Miller, 2002). Dopaminergic neuromodulation, however, declines during adult development (e.g., S.-C. Li et al., 2002). Thus, the current research evidence seems to suggest that less distinctive context representations in the PFC and the higher frequency of attentional lapses with advancing adult age both reflect senescent changes in dopaminergic neuromodulation.

2.3.5 Summary: Processing Fluctuations in Cognition

Processing fluctuations in cognition represent reliable interindividual differences that are in part independent of interindividual differences in the average level of performance. Furthermore, cognitive processing fluctuations are in particular informative about the status of the cognitive system in older adults. Across many cognitive tasks, older adults show stronger fluctuations in cognitive performances than younger adults. Aging-related differences in processing fluctuations are particularly strong in tasks that require executive functioning (i.e., attentional control). Neurobiological models relate attentional control to neuronal representations in the prefrontal cortex, which are modulated by the dopaminergic neurotransmitter system. The model of decreased neuromodulation predicts that old adults suffer an aging-related decrease in the efficacy of dopaminergic neuromodulation. This proposal is supported by empirical findings showing that aging-related differences in processing fluctuations are particularly high in tasks that require efficient neuromodulation of PFC control functions.

2.4 Aging and Processing Fluctuations in Sensorimotor Performance

In this section, the literature regarding processing fluctuations in sensorimotor performance is reviewed. The two main foci of argumentation concern the effects of aging on sensorimotor performance and the involvement of cognitive processing in sensorimotor tasks. In sensorimotor research, the concept of processing fluctuation is rarely addressed explicitly. A major outcome variable in studies of sensorimotor control is, however, the level of maladaptive intraindividual performance fluctuations (e.g., postural sway, which is a measure of moment-to-moment intraindividual variability). Therefore, a large section of the research regarding sensorimotor performances can be conceptualized within a framework guiding research on processing fluctuations.

2.4.1 Processing Fluctuations: Important Dependent Variables in Sensorimotor Research

Intraindividual performance fluctuations have always been a prominent issue in the research regarding sensorimotor performance, in particular in theories regarding the degrees-of-freedom problem in motor control (Bernstein, 1967). Newell (1998, p 65) reformulated the degrees of freedom problem in motor control in a single question: "How are the many degrees of freedom at different levels of analysis of the system harnessed to produce the movement form and variability associated with action?" In principle, there are so many ways to accomplish any given sensorimotor task that one of the key dependent variables in sensorimotor research is the degree of stability in the motor output. Consequentially, short-term variability in sensory motor output is the major dependent variable in studies investigating sensorimotor performance.

Fitts (1954) wrote a highly influential, classic article in which he introduced a formula relating the average amplitude of the movement, the average duration, and the amplitude variability of successive movements. This article clearly illustrates that intraindividual variability in performance is an inherent feature of motor control that cannot be separated from other types of performance measures such as the average performance or the peak performance. Intraindividual variability is still a major outcome measure in sensorimotor research in a variety of research topics like internal (i.e., feedforward) models of motor control (e.g., Wolpert, Gharamani, Jordan, 1995), human muscle coordination (Hamilton, Jones, & Wolpert, 2004), or timing of movements (Wing, 2002). One basic question that is central to these topics is the way in which the motor system reduces undesired intraindividual variability or, in other words, how the motor system handles processing fluctuations. [5] During the course of adult development this question becomes increasingly important. The decreasing efficiency of the motor system associated with aging presumably leads to increasing amounts of processing fluctuations.

2.4.2 Aging and Increased Sensorimotor Processing Fluctuations

There is ample empirical evidence that older adults are much more variable in their sensorimotor performance than younger adults. This statement can be generalized to a wide range of sensorimotor tasks such as arm movements, (e.g., Ketcham, Seidler, Gemmert, & Stelmach, 2002), force production (e.g., Vaillancourt & Newell, 2003), finger tapping (e.g., Woodruf-Pak & Jaeger, 1998), and postural control (see Woollacott, 2000, for review). Furthermore, higher levels

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[5] It has been proposed to focus not only on the question of whether there is any variability in motor performance but rather to ask the question of how variability in motor performance is organized over time (e.g., Newell, Broderick, Deutsch, & Slifkin, 2003; Slifkin & Newell, 1999; Thelen, 1995). In this view, the adaptiveness or maladaptiveness of performance variability is a matter of empirical inquiry.

of intraindividual variability associated with aging have not only been observed across different tasks but also in different task characteristics within the same sensorimotor tasks. Older adults show, for example, higher intraindividual variability than younger adults with regard to force initiation, deceleration, and the scaling components of motor movements (see Seidler & Stelmach, 1996, for review).

The origin of the aging-related differences in processing fluctuations in sensorimotor performance might stem from a number of sources. Explanations have not only been proposed on the basis of single mechanisms (e.g., lack of sensory integration, lack of muscle coordination, or distinct central processing deficits) but also in terms of broad mechanisms working on large numbers of systems involved in motor control (e.g., a decreased signal-to-noise ratio or a loss in physiological complexity).

2.4.3 The Importance of Postural Control in the Elderly Population

Postural control denotes the process by which humans regulate and maintain their upright posture. The postural control system has been chosen for investigation because of its fundamental importance for other sensory motor tasks (e.g., walking) and because it is particularly suited to illustrate processing fluctuations on different time scales.

Moreover, understanding processing fluctuations in postural control is an important topic in aging research for a number of reasons. High functioning postural control is a prerequisite for an independent living in old age. Any given daily activity that includes body movement, whether stepping on a stool, enjoying an evening stroll, or simply dressing oneself requires the successful regulation of the body's postural equilibrium. Furthermore, poor postural control performance is one of the major risk factors that can be used to predict the probability that a fall will occur (Brown & Woollacott, 1998; Woollacott, 2000). The incidence of falls is extremely high in the elderly population in comparison to younger adults. One in three people older than 65 years can be expected to suffer a fall within a twelve months interval (Lord et al., 1993). The costs for the treatment of fall related injuries in older adults are immense and place a heavy burden on public health care systems. In the United States about ten billion dollars were spent already 1992 for the acute care of fall-related fractures (Sattin, 1992). A demographical study in 1995 calculated that 12.000 lives are lost per annum due to fall-related injuries in the US (Van Fleet, 1995). Besides the direct physiological consequences of falls, there are also indirect psychological consequences, which also hamper the ability to lead an independent life in old age (Cummings & Nevitt, 1994). Large proportions of the older people who have already suffered a fall report that they are afraid of falling again. These feelings of fear lead to reduced daily activities and, consequently, to a loss in the confidence to live independently (Nevitt, Cummins, Kidd, & Black, 1989). Considering these facts together, it is of critical importance to gain an understanding how the postural control system controls processing fluctuations and how its regulatory mechanisms change during aging.

2.4.4 The Postural Control System

Successful postural control posits the body's center of gravity over its base of support to prevent falls. Traditionally, postural responses to disequilibrium have been thought to result from activation of reflex pathways by sensory information (e.g., Roberts, 1973). In contrast, modern views emphasize the specific importance of central processing in postural control (Massion, 1994; 1998; Woollacott & Shumway-Cook, 2002). In recent conceptualizations, the human postural control system is generally perceived as a complex system of interconnected subsystems involving motor processes, sensory processes, and cognitive aspects including the integration of different sensorimotor information (see Balasubramaniam & Wing, 2002, for review).

According to Massion (1998), the postural control system has two main functions. First, it computes and initiates the appropriate activation of muscles to allow the body to resist gravity and resulting ground reactions forces. Second, this system serves as an interface to the external world. The head posture, for example, is used as a reference frame to perceive moving objects in the environment. Although the force of gravity is constant, the upright posture is actively maintained because joints between body segments are free to move under external forces (Balasubramaniam & Wing, 2002). The resulting postural equilibrium is necessarily unstable and displays performance fluctuations.

One important tool for scientific investigations seeking to evaluate the performance of the postural control system is a computerized force platform that can be used to measure the participant's dynamic posturography. This procedure approximates the postural sway of a given individual, which is assumed to be inversely related to the individual's level of postural control ability at least when individuals are instructed to stand as still as possible[6]. Postural control is indexed by the drift or the fluctuations of the center of pressure (COP) across time. The COP is the resulting vector of all forces that participants apply on the platform to maintain their upright posture. In current studies, a variety of summary measures are used to quantify the amount of postural sway observed. All these measures relate the path traveled by the COP to a certain trial duration. Thus, the usual COP measures of postural control summarize moment-to-moment intraindividual fluctuations in postural control performance.

One broadly accepted perspective of how the postural control system works is that the system specifies a criterion set point and compares the internal representation of the body

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[6] Several authors have questioned this assumption. However, it is nevertheless a major research guideline regarding postural control (e.g., Van Emmerink, & Van Wegen, 2002).

posture with the actual or anticipated deviation from this set point (Massion, 1994; Merfeld, Zupan, & Peterka, 1999). If the deviation is large (depending on task constraints), corrective movements are initiated. To evaluate the efficacy of the postural control system, the variability of these movements is measured. In other words, low levels of moment-to-moment intraindividual fluctuations (i.e., low levels of processing fluctuations) conventionally characterize effective postural control.

Theoretical models of the postural control system propose that the system either monitors body movements by using feedback control based on perception or using feedforward control based on predictions of future deviations from equilibrium (e.g., Massion, 1994). There are empirical indications that both mechanisms are reflected in the fluctuations of the center of pressure. Based on diffusion plot analyses, Collins and De Luca (1993), for example, postulated that quite stance postural control is characterized by uncontrolled fluctuations within short frequencies (more than 10 Hz) and controlled performance on longer time scales (less than or equal to 10 Hz) based on sensory feedback.

It is assumed that feedback control is achieved by internally comparing incoming information from the senses with the desired criterion set point. Massion (1994, 1998) describes the postural control system as being dependent on sensory information from at least three distinct sensory systems: the visual system, the vestibular system, and the somatosensory system. Sensory information is integrated centrally and a mental representation of the body position is generated concurrently. A variety of studies revealed that a reduction in sensory input always leads to an increase in postural sway but not necessarily to a higher rate of falls (e.g., Manchester, Woollacott, Zederbauer-Hilton, & Marin, 1989). Therefore, it is a common assumption that the interplay between sensory systems in postural control creates compensatory redundancy. Thurner, Mittermaier, Hanel, and Ehrenberger (2000) used dynamic-systems analysis to differentiate between the influences of the three sensory systems (i.e., the vestibular, the somatosensory, and the visual system) on the postural regulation in the stable up-right standing position. They showed that the contributions of the sensory systems were reflected in the overall complexity of the fluctuations in the time-evolution of corrective movements. Moreover, if all sensory systems were fully functional, each system worked on its own differentiable time scale. The complexity theory of physiological signals hypothesizes that these multiple rhythms in postural fluctuations that are introduced by the different sensory systems would enhance the adaptivity of the postural control system (Lipsitz, 2002). Efficient postural control, however, demands the effortful integration of the different sensory inputs (e.g., Jeka, Oie, & Kliemel, 2000; Mergner & Rosemeier, 1998). Furthermore, dynamicly weighting and reweighting of the sensory contributions to the postural control system is needed in correspondence to a changing environment (Peterka, 2002; Peterka & Loughlin, 2004). Internal modeling of a mental representation of the body's position in space is one way for the postural control system to achieve these goals (Perterka & Loughlin, 2004; Wolpert, Gharamani, & Jordan, 1995).

Due to the utilization of internal representations, the postural control system can make use of feedforward control mechanisms. In contrast to the feedback control based on sensory input, feedforward control predicts the new body position by dynamic mental modeling of the body's position and changes of that position in time (Massion, 1998). This mechanism promotes fast and accurate error detection by rapid comparisons of the desired state of the system as determined by feedforward control to the perceived state derived from sensory feedback-loops (Wolpert, et al., 1995). The inclusion of feedforward mechanisms in models of motor control resolves a number of fundamental problems in computational motor-control (Wolpert, et al., 1995). For instance, feedback control is too slow to adapt the body's position to fast movements. A feedforward model can use the motor output flow (i.e., the efference copy of the motor commands) to anticipate sensory consequences (Blakemore, Goodbody, & Wolpert, 1998; Mittelstädt, 1998). Thus, by using feedforward control, the outcome of an action can be estimated before sensory feedback is available (Miall, Weir, Wolpert, & Stein, 1993).

The utilization of feedforward control and the strong demand for sensory integration suggests that postural control depends strongly on central processing (Mittelstädt, 1998). In recent years, efforts have been made to identify the underlying brain regions directly where these processes might take place. Findings obtained from studies that involved stroke patients who suffered from postural instability suggest that the internal body representation probably implicates parietal cortical functions (Perènnou, et al., 2000; Wolpert, Goodbody, Husain, 1998). In particular, the temporoparietal junction (TPJ) – a part of the polymodal sensory cortex – was found to play a fundamental role in the control of body sway. The polymodal sensory cortex is thought to be a nodal point for the neural network underlying mental body representations because of its involvement in the integration of different sensory inputs and the combination of afferent and efferent information (Perènnou, et al., 2000). Furthermore, the temporoparietal junction seems to play a crucial role in the detection of changes in the sensory environment (Downar, Crawley, Mikulis, & Davies, 2000). In addition to maintaining the internal body representation in 3D space, parietal lobe functions may also underlie covert preparatory motor attention (Rushworth, Johansen-Berg, Göbel, Devlin, 2003). This might be analogous to their role in visual attention, where parietal regions are involved in the coordination of overt (i.e., controlled) attentional processes and covert (i.e., stimulus driven) attentional processes (Posner, Walker, Friedrich, & Rafal., 1987; Serences et al., 2005).

Interestingly, the study done by Perènnou, et al., (2000) found that lesions in prefrontal cortical areas, which are associated with attentional control (e.g., Duncan & Miller, 2002), did not hamper postural control performance. The postural task used in this study, however, was relatively easy (i.e., participants were sitting). Ouchi, Okada, Yoshikada, Nobezawa, and Futatsubashi (1999) showed that prefrontal areas, in particular the dorsolateral prefrontal cortex, are activated in the postural control of the upright standing if the task demands are high. Higher activations of the dorsolateral prefrontal cortex (DLPFC) and a stronger effective connectivity of the DLPFC to premotor areas have been found to be key features of directing overt (i.e., controlled) attention to sensorimotor performance in finger-tapping tasks (Rowe, Friston, Frackowiak, 2002; Stephan et al., 2002). Speculatively, that fact that DLPFC is involved in high demanding postural control tasks but not in low demanding postural control tasks indicates a shift from a more automatized postural control strategy to a strategy which uses the supervision of attentional control to regulate the body sway. Thus, if the sensory input is disturbed or the postural position is challenging (e.g., standing in tandem position with eyes closed) and when postural control demands are high as a consequence of this, people are more likely to pay attention to the actual postural control process (Woollacott & Shumway-Cook, 2002).

However, the particular demands of a given sensorimotor task are relative and depend on the efficiency of the individual's postural control system. In the next sections, empirical evidence will be reviewed to show that the postural control system of older adults is less efficient than that of younger adults. This aging-related decline in efficacy observed in older adults has implications with regard to the difficulty level of postural control tasks and the involvement of cognitive processing.

2.4.5 Aging-Related Changes in Postural Control

The efficiency of postural control systems decreases with aging (Choy, Brauer, & Nitz, 2003; Maki & McIlroy, 1996; Woollacott, 2000). Older adults show higher moment-to-moment processing fluctuations of the COP than young adults. Adult age differences in postural sway are stronger and occur earlier in life the more the sensory input is disturbed (e.g., greater differences in eyes-closed conditions than in eyes-open conditions) and the more difficult the postural task is (e.g., greater differences in tandem stand than in shoulder-width stand; see, Woollacott, 2000, for a review). Parallel to the observations at the overall performance evidence has been gathered about structural changes associated with aging in different subsystems involved in postural control. Aging is associated with negative effects on basically all of these subsystems including muscosceletal, sensory, and central processing components (see, Maki & McIlroy, 1996;

Woollacott, 2000, for review). In this section, aging-related changes in subsystems will be reviewed first before the dynamic aspects are elaborated with regard to their importance for processing fluctuations on different time scales.

2.4.5.1 Changes in Subsystems

There is ample empirical evidence demonstrating an aging-related reduction in muscle strength, which is associated with losses in muscle fibers and the number of motor neurons (Vandervoort, 1992). Additionally, muscles of older adults contract more slowly than muscles of young adults. This presumably impedes the swiftness with which postural responses to perturbations can be carried out (Vandervoort, 1992). Older adults, however, do not only show slower muscle activation patterns but sometimes also activate different muscle groups than younger adults to accomplish the same postural tasks. For example, older adults activate both agonist and antagonist muscles more frequently than young adults (Woollacott, Shumway-Cook, & Nasher, 1986). They are also more likely to react to postural perturbations with a hip strategy than young adults even in response to small perturbations (Manchester et al., 1989). In contrast, young adults typically initiate hip movements when the threats to their balance are very large.

Aging-related changes deprive the functional efficacy of all sensory systems engaged in postural control. The visual system, for example, displays reduced acuity, contrast sensitivity, depth perception, and dark adaptation (Verillo & Verillo, 1985). The vestibular system shows a progressive loss of labyrinthine cells, vestibular ganglion cells, and nerve fibers. There is a decreasing functionality of the vestibular system as indicated by changes in the vestibular-ocular reflex, which is associated with the neuronal losses (Paige, 1991). Reduced proprioceptive information in older adults in comparison to younger adults have been demonstrated with regard to a reduced sense of vibration as well as an impairment in sensing the positions of joints (MacLennan, Timothy, & Hall, 1980; Stelmach, Goggin, & Armheim, 1988). Furthermore, the postural control system of older adults is more dependent on the availability of full sensory input (e.g., Shumway-Cook & Woollacott, 2000). Aging-related differences in processing fluctuations in postural control are higher the more sensory information is disturbed (e.g., Shumway-Cook & Woollacott, 2000; Woollacott et al., 1986). These empirical findings indicate a lower level of redundancy in the sensory input in older adults in contrast to younger adults (e.g., Woollacott et al., 1986). It has been hypothesized that within the postural control system of elderly people, sensory information from different modalities can no longer compensate for each other due to the lack of accuracy of the sensory information (Manchester et al., 1989).

In addition to aging-related declines in peripheral sensory and muscular systems, there are a number of changes in the central and peripheral nervous systems. These changes may have an impact on the motor execution aspects as well as on central processes involved in postural control. Specific aging-related changes that have been observed within the motor system include a severe loss of giant pyramidal Betz cells within the motor cortex, a progressive aging-related loss of neurons, and a depletion of neurotransmitters, such as dopamine within the basal ganglia, and changes in the dendritic tree of motor neurons in the spinal cord (Scheibel, 1985). Furthermore, aging-related declines in the parietal cortex, the cortical region underlying the internal body representation in space, are evident at neurochemical (Inoue et al., 2001; Kaasinen et al., 2000), neuroanatomical (Tisserand et al., 2004), and functional levels (e.g., Labyt et al., 2003).

2.4.5.2 Age Differences in the Dynamic Aspects of Postural Control

Given the strong aging-related losses in system components reviewed above, the loss of complexity theory would predict that these deficits should strongly hamper optimal sway regulation. These deficits should manifest themselves in the complexity of the output signal over time (Lipsitz, 2002; Vaillancourt & Newell, 2002). Postural control of the simple upright stand is a homeostatic task. It requires the organism to fluctuate as little as possible around an equilibrium point. Thus, high complexity is assumed to be beneficial for the regulation of the body sway (Vaillancourt & Newell, 2002). In concordance to such predictions, empirical studies demonstrated aging-related losses in the complexity of the time-evolution of the postural control output signal during regular upright stand (McCleaghan et al., 1996; Lipsitz, 2002; Thurner, Mittermaier, & Ehrenberger, 2002). For instance, Thurner et al. (2002) calculated the overall complexity of the postural control signal across time and found a decrease of complexity associated with age. The signal complexity was negatively correlated with measures quantifying the overall amount of sway amplitude (i.e., moment-to-moment processing fluctuations). They concluded that complex movement patterns are in fact indicators for active postural sway reduction. Their findings also suggest that an aging-related decline in postural control is not only due to declines in single subsystems, but also arises because the harmonious interplay between subsystems is disturbed.

In older adults, the reduction in system components reflects a reduction of effective postural control mechanisms, which could lead to a greater susceptibility to perturbations from inside or outside the organism. Lipsitz (2002) argued that complex systems are able to initiate a focused response to a perturbation on a number of different time scales. A loss of complexity in postural control hinders the fast and accurate execution of an appropriate response to a given perturbation, thereby leading to maladaptive responses (i.e., processing fluctuations). Another explanation put forward by Thaler (2002) states that the loss of complexity in the time-evolution of postural control performance that is associated with aging indicates the inability of the aged system to detect small perturbations. This explanation squares nicely with neural modeling accounts of aging-related differences in the signal-to-noise ratio. According to S.-C. Li and colleagues (e.g., S.-C. Li et al., 2001), the low signal-to-noise ratio in the elderly – presumably caused by deficient catecholaminergic neuromodulation – leads to a less distinctive mental representation of stimuli that renders different stimuli less differentiable. In case of the postural control system these findings would implicate fuzzier representations of the sensory information and a loss of precision in feedforward control in older adults in comparison to younger adults. Furthermore, a low signal-to-noise ratio may impair the integration and weighting of sensory inputs.

These two theoretical positions are not mutually exclusive. It is probable that both the reduced detection capacity and the decreased adaptivity of the postural control system contribute to greater processing fluctuations in older adults than younger adults. Both perspectives would predict that small perturbations are more likely to drive the old postural control system to its limits of performance than they would drive a young system. As long as one can expect perturbations to occur from minute to minute or from day to day, processing fluctuations in postural control should also be evident from minute-to-minute and from day-to-day.

Perturbations to the system and the associated processing fluctuations can stem from a number of possible sources. In lifespan psychology, it has been suggested that aging-related declines in sensory/sensorimotor performances are associated with functional losses in cognitive performances (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994).

2.4.6 The Interaction of Cognition and Sensorimotor Performance: The Relation to Aging

Several cross-sectional comparative studies have demonstrated higher correlations between sensory/sensorimotor functions and cognitive functions in older adults than in younger adults (Anstey, Lord, & Williams, 1997; Anstey & Smith, 1999; Baltes & Lindenberger, 1997; Christensen, Macinnon, Korten, & Jorm, 2001; Lindenberger & Baltes, 1994). In these studies, sensory variables included vision and hearing and sensorimotor variables consisted of measures like grip strength, strength in the lower limbs, or forced expiratory volume. Using hierarchical linear regression analyses, Baltes und Lindenberger (1997) found that the amount of interindividual variance in intellectual functioning that was related to sensory functioning increased from 11% in 25- to 69-year olds to 31% in old age (70-103 years). Cross-sectional analyses consistently found a common factor explaining large portions of aging-related related variances in sensory/sensorimotor performance and cognitive functioning. Specific factors relating specific variables like vision or grip strength uniquely to cognitive functioning have also been obtained in some studies (e.g., Anstey, Hofer, & Luszcz, 2003a, 2003b; Christensen et al., 2001). There seems to be general agreement, however, that large portions of aging-related changes in sensory/sensorimotor functions and cognition might share an underlying common cause. Although this claim cannot directly be validated purely based on cross-sectional results (Hofer & Sliwinski, 2001; Lindenberger & Pötter, 1998), it is partly supported by longitudinal analyses (Anstey, Hofer, & Luszcz, 2003a, 2003b; Ghisletta & Lindenberger, 2005). For example, Ghisletta and Lindenberger (2005) could demonstrate lead-lag relations between vision and perceptual speed in a sample of older adults observed up to six years.

Theoretically, possible causes of the stronger link between sensorimotor performances and cognitive performances in older adults have been suggested on multiple levels (K. Z. H. Li & Lindenberger, 2002). Ontogenetic common-cause explanations suggest (Baltes & Lindenberger, 1997; Lindenberger et al., 2000) that one aging-associated, biological factor like the decreased efficacy of the dopaminergic system (S.-C. Li, Lindenberger, et al., 2001) contributes a substantive share to the aging-related decline across cognitive and sensorimotor domains. If an aging-related decline in the efficiency of dopaminergic neuromodulation impairs both types of functions, as the computational results from S.-C. Li et al. (2001) suggest, then an increasing bearing on these functions with advancing age leads to higher correlations between them (e.g., S.-C. Li, 2002; S.-C. Li & Lindenberger, 1999).

Another explanation for the strong relationship between cognitive and sensorimotor performances in old adults has been suggested on the microgenetic level and can be labeled cognitive permeation hypothesis (e.g., Krampe & Baltes, 2003; Lindenberger et al., 2000). In this perspective, the focus is on the differential allocation of resources in a multi-task setting. Decreases in perceptual and cognitive processing efficacy associated with aging have been interpreted as the results of the general decline in the overall resources that can be invested into sensorimotor or cognitive tasks at any moment (e.g., Krampe & Baltes, 2003; Lindenberger et al., 2000). Interdependence between domains arises specifically under dual task conditions if limited resources have to be invested into one task but are also needed for the execution of a second task. Within dual-task situations, fluctuating allocation of resources from one task to the other could induce correlations between moment-to-moment fluctuations in both tasks. Moreover, executive control functions that are important for differential resource allocation show a clear functional decline in old age (Mayr & Liebscher, 2001; Verhaeghen & Cerella, 2002, for reviews).

Both explanations mentioned are not mutually exclusive but are simply linked to different levels of analyses. The aforementioned loss in efficient neuromodulation during aging and its consequences (e.g., S.-C. Li et al.,2001) might strongly impair sensorimotor as well as cognitive functions. The allocation of attentional resources (i.e., the use of attentional control) to sensorimotor functions has been considered a compensatory mechanism to enhance the functionality of the sensorimotor system in the face of these aging-related losses (Krampe & Baltes, 2003; K. Z. H. Li & Lindenberger, 2002). It is important to note, however, that this compensation does not need to be a conscious decision but might arise from unconscious adaptations of the elderly to their perceived losses in sensorimotor capacities (Lindenberger et al., 2000). The interaction between cognitive and sensorimotor demand in postural control is rarely investigated with correlational methods but rather with dual-task experiments. Because of the important role that dual-task studies play in the theoretical thinking about the interaction between postural control and cognition their rational and the main empirical findings are described in the next section.

2.4.6.1 Dual-Task Interactions between Postural Control and Cognition

Postural control is a highly practiced daily task for healthy younger and older adults and is usually effectively performed without overt (e.g. controlled) attentional control in most circumstances. Moreover, postural control in daily situations routinely takes place while at least one other concurrent task is being performed (e.g., standing while thinking or standing while talking). As already mentioned above postural control might, however, involve attentional control if the postural task constraints are challenging (e.g., balancing in the dark or with a difficult standing position), but also when attentional interference between postural control and cognitive processes is high (Woollacott & Shumway-Cook, 2002). Empirical evidence with regard to dual-tasking postural control is paralleled by cognitive and neurocognitive evidence on attentional limitations in performing multiple tasks at the same time that has been gathered in other fields of psychological research (Pashler, 1992; Posner, 1980).

The attentional demand for maintaining postural equilibrium is typically examined with a dual-task paradigm, which presumes that cognitive functions and postural control compete for limited attentional capacity (see K. Z. H. Li & Lindenberger, 2002; Woollacott & Shumway-Cook, 2002, Schäfer et al., in press, for reviews). In most empirical applications, attentional capacity has been thought of as a metaphor for general cognitive resources, which are needed to different degrees to perform any sensorimotor or cognitive task (Woollacott & Shumway-Cook, 2002). The general resource model of dual-task postural control predicts that when one needs to maintain postural stability while performing a concurrent cognitive task, attention is divided between the sensorimotor and cognitive tasks. Postural stability under dual-task conditions may decrease in comparison to single-task performance to varying degrees according to the demands of concurrent cognitive processing. Sharing of attentional resources between the two domains of functioning reduces the amount of attention that is available for the regulation of postural stability.

Aging is associated with a reduction of the efficacy of sensory, muscular, central processing components of the postural control system and maladaptive changes in the time-evolution of the postural control signal (Thurner at al., 2002; Woollacott & Shumway-Cook, 2002). Losses at these various levels presumably lead to a higher need for attentional control in sensorimotor functioning of older adults compared to young adults (see K. Z. H. Li & Lindenberger, 2002; Schäfer et al., in press, for reviews). Aging has, however, disproportionally strong effects on executive function (see Mayr & Liebscher, 2001; Verhaeghen & Cerella, 2002, for reviews), and prefrontal brain regions involved in these processes show strong age-related declines (e.g., Raz et al., 2005; Sowell et al., 2003). Therefore, aging-related losses in prefrontal executive functions might impair the successful employment of attentional resources for effective sway regulation (Maki, Zecevic, Bateni, Kishenbaum, & McIllroy, 2001). One might say that, on the one hand, older adults are more in need of attentional control of sensorimotor performance than young adults but, on the other hand, they are less able to use attentional control than young adults. Such reciprocal influences are assumed to result in increased interdependence of cognitive and sensorimotor processes with advancing age (e.g., Baltes & Lindenberger, 1997; S.-C. Li et al., 2001; Lindenberger & Baltes, 1994; Lindenberger et al., 2000).

2.4.6.2 The U-shaped Curve Linking Postural Control and Cognitive Demand

Although the general notion of attentional resource sharing between postural control and cognition as such is convincing and straightforward, the empirical evidence is far from being unequivocal. In line with the prediction from the common resource view, some studies showed that dual-tasking posture control has resulted in increments of postural sway in comparison to single-task postural control (Andersson, Yardley, & Luxon, 1998; Condron & Hill, 2002; Maylor & Wing, 1996; Melzner, Benjuya, & Caplanski, 2001; Mitra, 2003; Pellecchia, 2003). However, other studies primarily but not exclusively involving young adults found that performing a concurrent cognitive task while standing actually decreased postural sway (Andersson, Hagman, Talizandeh, Svedberg, & Larsen, 2002; Dault, Frank, & Allard, 2001; Deviterne, Gauchard, Jamet, Vancon, & Perrin, 2005; Ehrenfried, Guerraz, Thilo, Yardley, & Gretsy, 2003; Riley, Baker, & Schmit, 2003, 2005; Swan, Otani, Loubert, Sheffert, & Dunbar, 2004).

The dual-task benefit on postural control can be understood by considering the role of the secondary task in directing the individual's attentional focus. It is a common practice in the research of postural control to instruct the participants to stand as still as possible. With such an introduction, it is very likely that the participants direct their attention internally to the actual execution of the relatively automatized postural control process. A number of studies have consistently found that postural sway increased when the participants' attention was directed to postural control performance in internal-focus conditions as opposed to external-focus conditions where attention was diverted to a supra-postural task (McNevin & Wulf, 2002; Riley, Stoffregen, Grocki, & Turvey, 1999; Wulf, Mercer, McNevin, & Guadagnoli, 2004). In line with these findings, the constrained action hypothesis proposes that directing attentional control to a highly automatized process, such as postural control under regular conditions, reduces the efficacy of this process (Wulf, McNevin, & Shea, 2001).

However, it should be kept in mind that the postural control process may still require some attention to facilitate multi-sensory integration and the generation of motor commands (cf. Wolpert et al. 2001). The more challenging the postural task, the stronger is the involvement of cognitive processes (e.g., Redfern, Jennings, Martin, & Furman, 2001; Shumway-Cook & Woollacott, 2000; Teasdale & Simoneau, 2001). Thus, it seems plausible that with increasing cognitive demand of the secondary cognitive task the likelihood of attentional resource competition between postural control and the cognitive task increases. With sufficiently high dual-task demands (i.e., cognitive and sensorimotor demands), the beneficial effect of providing an external focus is overtaken by this resource competition and postural control is disturbed. Therefore, several authors have speculated that the relationship between postural control and cognition is U-shaped (Deviterne et al., 2005; Riley et al., 2003, 2005; Vuillerme et al., 2000). Given older adults' more limited attentional capacity and their declining efficacy of the postural control system, attentional competition between postural and cognitive tasks should emerge faster in older than in younger adults. Thus, it can be predicted that the rising part of the U-shaped function relating cognitive demand to postural control would already emerge at lower levels of cognitive task difficulty in older adults than in young adults.

Thus far, only one study has demonstrated the U-shape function of the interaction of postural control and cognition empirically. Huxhold, Li, Schmiedek, and Lindenberger (2006) varied the cognitive demand of the secondary task in a monotonically increasing manner. Young and old participants' postural control performance was assessed in a standing only condition and in three dual-task conditions differing in the demand of the secondary cognitive task. The participants performed an easy perceptual task, a choice-reaction-time task, and a demanding n-back working-memory task. The results are displayed in Figure 2.

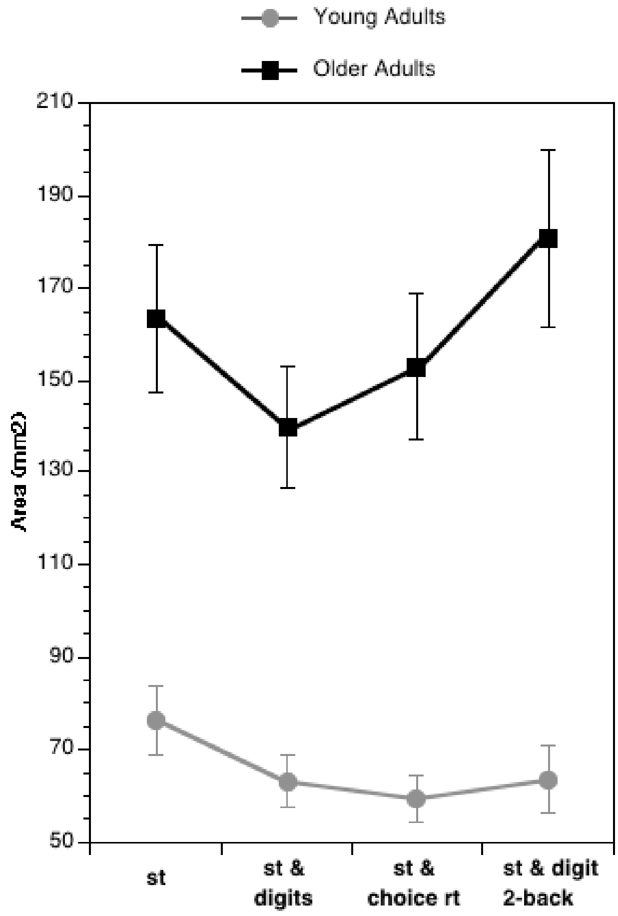

Figure 2. *The U-shaped Relation between Cognitive Demand and Postural Control as a Function of Age.*
Note: st = standing only; st & digits = standing and watching digits; st & choice rt = standing and performing a choice-reaction-time task; st & digit 2-back = standing and performing a verbal 2-back working memory task.

In line with the theoretical predictions, the authors observed a U-shaped relationship between cognitive demand and postural control performance. The perceptual task of low cognitive demand was associated with decreased postural sway in both age groups in contrast to the simple standing condition. This effect can be attributed to the overt focus of attention being directed away from actual postural control in the low cognitive demand condition. A shift of the locus of attention from an internal focus to an external focus allowed the postural control system to regulate postural sway in a more automatic, proceduralized way. In older adults, however, the beneficial effect of the secondary task in providing an external focus of attention was overtaken by the negative effect of resource competition as the cognitive demand of the secondary task increased. In contrast, due to their relatively high level of cognitive capacity, young adults did not experience increasing resource competition with the same nominal difficulty level of the cognitive task and their postural control performance did not worsen. It has been argued that simple standing is so highly automatized in young adults that increasing the cognitive load might have been insufficient to tax their postural control system. It is possible that the demand of the sensorimotor task has to be very challenging to observe the curvilinear relation in young adults. For example, significant dual-task costs in cognitive performance have been found even in young gymnastics experts while they were standing on one leg (Vuillerme & Nougier, 2004).

The findings reported by Huxhold et al. (2006) imply that the interactions in multi-task situations between the focus of attention, the sensorimotor and the cognitive demand of the postural control task, and the capacities of the individual in both domains are complex. These interactions determine the degree of interdependence between sensorimotor and cognitive performances within a given situation. Due to their reduced capacities in both domains of functioning it can be expected that older adults are more likely to show resource competition than young adults.

2.4.7 Summary: Aging and Processing Fluctuations in Sensorimotor Performance

The postural control system is highly complex and involves complex interactions between motor, perceptual, and cognitive processes. One of the system's main functions is to reduce processing fluctuations to keep the body's postural equilibrium. In older adults, the different subsystems of postural control are less efficient and their interplay is less harmonious than in young adults. In the elderly processing fluctuations in postural control are stronger than in younger persons. Relatedly, a stronger correlative interrelationship between sensory/sensorimotor functioning and cognitive performances has been observed. Theoretical explanations of these findings either emphasize a common factor account such as the decreasing efficacy of catecholaminergic neuromodulation or a cognitive permeation perspective. The latter is commonly investigated with a dual-task paradigm. In dual-task situations postural control can either benefit or suffer from a secondary cognitive task depending on the demand of the cognitive or postural task and the individual's capacities in both domains. Due to their limited capacities older adults are more likely to experience dual-task costs under task conditions in which younger adults would not necessarily show such costs. Finally, it needs be noted that the cognitive permeation view and the common factor perspective may not be mutually exclusive but rather represent different levels of analyses.

2.5 Sex Differences in Postural Control

Sex differences in postural sway regulation have been studied less often than age differences. Although the empirical evidence is not completely conclusive, there is a trend in the literature showing that young and middle-aged women manage processing fluctuations in postural control more efficiently than young and middle-aged men (Ekdahl, Jarnlo, & Andersson, 1989; Farenc, Rougier, & Berger, 2003). In older populations, the empirical results are more mixed, sometimes favoring men (Wolfson, Whipple, Derby, Amerman, & Nasher, 1994), sometimes favoring women (Kollegger, Baumgartner, Wöber, Oder, & Deecke, 1992), and sometimes with no differences between the sexes (Maki, Holliday, & Fernie, 1990). The integration of these divergent findings is difficult. Theoretical explanations are also diverse. One potential explanation focuses, for example, on the sex difference in height. On average, women are smaller than men. This implies that the center of gravity of the body is higher in men than in women. A higher center of gravity is harder to control than a lower center of gravity. This explanation is in accordance with the finding that sex differences disappeared when interindividual differences in height were statistically controlled for (Hageman, Leibowitz, & Blanke, 1995). More interestingly, there is some evidence that the male postural control system is more dependent on visual information than the female system. Two studies showed that young and older men were more affected by the exclusion of vision than young and older women (Golomer, Dupui, & Monod, 1997; Kollegger et al., 1992). However, older women performed less well than their male counterparts when they had to react actively to external perturbations to their base of support (i.e., forward and backward translations of the support base; Wolfson et al., 1994). In the light of a general female advantage with respect to sensory processing efficiency in postural control, it was concluded that sex differences with regard to perturbed postural control might arise from muscosceletal factors like muscle strength.

The empirical evidence on sex differences in postural control is not conclusive and the question whether women or men show a stronger involvement of cognition in postural control has not yet been asked. However, there is some indication that visual processing is more important for men than for women in the regulation of body sway. Furthermore, as reported above older adults have a stronger need for visual control than younger adults. Bearing these two empirical findings in mind, it seems plausible to expect that older men would enhance their inefficient visual processing by attentional control more than older women. This speculation, however, requires empirical corroboration.

2.6 Processing Fluctuations on Multiple Time Scales

It is possible to understand processing fluctuations as being a consequence of perturbations to a given functional system. It has been already mentioned that perturbations can either stem from inside or from outside the organism; or from an interaction between both sources. The loss-of-complexity theory hypothesizes that physiological systems of older adults are more vulnerable to perturbations than those of young adults (Lipsitz, 2002). The model of decreased neuromodulation also implies that older adults are less resilient to perturbations than young adults, given their higher level of intrinsic noise in information processing (S.-C. Li et al., 2001). Both perspectives predict that older adults will display higher amounts of processing fluctuations in response to smaller perturbations to their functional systems than young adults would do. In this context, it has to be noted first that these perturbations can occur on various time scales and second that perturbations on different time scales can have different sources. Ward (2002), for example, was able to successfully simulate the empirical characteristic patterns of repeated choice-reaction-time trials in log-log space by assuming three component processes (i.e., preconscious, unconscious, and conscious processes) fluctuating on short, intermediate, and long time scales, respectively. The empirical studies that have been reported in the sections above focused on processing fluctuations in sensorimotor and cognitive performances occurring from moment to moment. Studies examining fluctuations from day to day or from week to week are rather rare, with only a few exceptions.

Rabbitt et al. (2001) investigated processing fluctuations from moment to moment and from day to day in reaction times (RT) on a number of choice-reaction-time tasks in an age-graded sample ranging from 50 to 79 years of age. They trained their participants to their maximum levels of performance and were therefore able to examine processing fluctuation without confounding them with performance changes due to learning. Their main findings showed that people with lower scores on a fluid intelligence test displayed higher performance fluctuations within a day and across days. When interindividual differences in fluid intelligence were taken into account, age was no longer related to the level of processing fluctuations on both time scales. Simulation analyses revealed that day-to-day processing fluctuations were greater on average than could be expected by considering within-day moment-to-moment fluctuations. However, among people with low fluid intelligence scores, within-day fluctuations explained all variance in day-to-day processing fluctuations. This was not the case for participants with high fluid intelligence scores, who expressed more day-to-day performance fluctuations than could be predicted by their level of within-day fluctuations. In this context, the authors suggested the possibility that high levels of within-day processing fluctuations of low performers in the intelligence test may have masked their day-to-day processing fluctuations. Interestingly, in a follow-up analysis including the full range of the data (Rabbitt et al., 2001), Ram et al., (2005) demonstrated that learning across days not only reduced average reaction times but also moment-to-moment processing fluctuations. Therefore, it can be concluded that the amount of daily processing fluctuations in cognitive performance may not only be determined by the level of processing fluctuations on shorter time scales, but that it can also be associated with chronological age, fluid intelligence, and learning.

Nesselroade and Salthouse (2004) examined within-session and between-session fluctuations of two perceptual-motor tasks that were administered on three occasions within two weeks to a sample of 204 participants with an age-range from 20 to 90 years. In their analyses, within-session fluctuations were of larger magnitude than between-session fluctuations. Day-to-day processing fluctuations, however, were of equal magnitude as performances differences associated with 12 to 27 years of chronological age differences. This finding implies, for instance, that on a good day an average 70-year old person may perform like an average 43-year old person.

Based on the reviewed literature regarding moment-to-moment processing fluctuations in sensorimotor performance, one may expect that processing fluctuations in sensorimotor performance should be correlated with measures of cognitive performances at least in the elderly (see K. Z. H. Li & Lindenberger, 2002; Schäfer et al., in press, for review). Thus far, only one study (S.-C. Li, Aggen et al., 2001) explicitly addressed the relationship of processing fluctuations in sensorimotor functioning on longer time scales (i.e., weeks) with cognitive functioning. S.-C. Li, Aggen et al. (2001) used measures of intraindividual fluctuations in walking performance to predict intraindividual fluctuations and mean level of spatial and verbal memory in a sample of older adults (mean age = 75.71 years). All measures were assessed biweekly across approximately seven months. They found that, on average, intraindividual fluctuations in sensorimotor performance and intraindividual fluctuations and the mean level of cognitive performance were moderately correlated. If the mean level of walking performance was taken into account, weekly fluctuations in walking performance measured in number of steps still uniquely contributed 18% of the interindividual differences in average text memory performances. It remained open, whether cross-domain associations between intraindividual fluctuations in walking performance can be generalized to other domains of sensorimotor functioning and whether such cross-domain associations could also be observed in younger adults. This dissertation attempts to answer these two questions.

So far, daily fluctuations in postural control performance have not yet been studied. In general, time-related changes in postural control are rarely investigated, presumably because of the labor-intense measurement procedure. Dault and Frank (2004), however, reported repeated measurements of postural control performance across several trials (i.e., 6 trials) and addressed time-related effects explicitly in their analyses. The authors did not find any trends. Processing fluctuations were not considered in the analyses.

This lack of empirical evidence is surprising, given the high importance of efficient postural control for independent living in old age. Efficient postural control requires the successful regulation of processing fluctuations. Arguably, perturbations to the postural control system can occur on many different time scales. As mentioned above, the postural control system of older adults is more vulnerable to processing fluctuations than that of young adults due to the severe structural and functional losses in all subsystems. However, long-term trends (e.g., learning trends across days), the strength of slow processing fluctuations (e.g., day-to-day time scale), and the relationship between processing fluctuations on different time scales (e.g., the relationship between moment-to-moment and day-to-day processing fluctuations) in postural control and potential age differences in all three aspects have not received much scientific attention.

This dissertation thesis attempts to resolve this apparent blind spot in the body of knowledge regarding the postural control system by examining age differences in processing fluctuations in postural control on different time scales. Furthermore, it seeks to identify possible correlates of processing correlations. Between-person analyses have shown that the efficacy of sensorimotor processes among older adults depends more on attentional control than it does among younger adults (e.g., K. Z. H. Li & Lindenberger, 2004). Therefore, this thesis focuses on the coupling between processing fluctuations in postural control and cognitive functioning. For reasons spelled out in more detail in the next section, the empirical investigation was not based on between-person analyses but on analyses on the within-person level.

2.7 A Methodological Caveat Regarding Between-Person Analyses

Processing fluctuations in postural control could possibly stem from a number of sources. From a psychological perspective, it has been suggested that inefficiencies in sensorimotor functioning associated with aging might be related to cognitive functioning (cf. K. Z. H. Li & Lindenberger, 2004). Thus far, the correlational evidence demonstrating a strengthening of the interrelation between sensory/sensorimotor performances and cognitive functioning that is associated with aging was primarily based on comparisons of correlational patterns of interindividual differences. In contrast, theoretical explanations of these findings such as the common cause hypothesis or the cognitive permeation hypothesis focus on processes evolving within individuals across time (cf. K. Z. H. Li & Lindenberger, 2004). Several authors in the domain of lifespan psychology have pointed out for a long time that there is a widespread mismatch in developmental psychology between theory and empirical support (e.g., Baltes et al., 1988). In most correlational approaches in developmental psychology, intraindividual variability is substituted with interindividual differences to answer questions about within-person processes. In recent years, it has been demonstrated formally and by means of simulation studies that such substitutions are only legitimate if two criteria are met (e.g., Molenaar, 2004; Molenaar et al., 2003).

The first criterion is sometimes termed variation equivalence and describes an empirical situation in which the same set of processes causes interindividual differences and intraindividual variation in the variables under study (Lindenberger & Oertzen, 2006; Lövdén & Lindenberger, 2004). Formally such a situation is only guaranteed under some very stringent mathematical conditions and dependent on the nature of the governing processes (e.g., are these processes approximately Gaussian or do they contain cyclic trends? cf. Molenaar, 2004). Assuming that the underlying processes are approximately Gaussian, equivalence between between-person and within-person variability is formally guaranteed if the processes under study are stationary (Molenaar, 2004). This requires, for example, that the covariance structure of the variables under study is invariant over time. However, it is part of the very nature of an increasing interrelationship between sensory/sensorimotor and cognitive variables with aging that the covariance structure undergoes a developmental change. If variation equivalence cannot be assumed *a priori*, between-person analyses do not generalize to within-person interrelations (e.g., Lindenberger & Oertzen, 2006; Molenaar, 2004; Molenaar et al., 2003). Therefore, it is an open empirical question whether the observed age-dependent between-person covariance structures can be generalized to within-person structures.

The second criterion that has to be met to legitimize the use of interindividual variance analyses to investigate within-person theoretical processes has been termed sample homogeneity (Lindenberger & Oertzen, 2006; Lövdén & Lindenberger, 2004). Sample homogeneity refers to the assumption that the relevant structural relations between the variables under study are approximately equivalent between different persons. For example, if a hypothetical between-person correlation of postural control and spatial working memory is .20, it is assumed that every single individual in the sample has a within-person correlation that does not significantly differ from .20. It becomes instantly apparent that such a situation requires the absence of any person-specific mediating factors. Lindenberger and Oertzen (2006) have argued that the assumption of sample homogeneity in general violates the notion of differential developmental change propagated by lifespan psychology (e.g., Baltes et al., 1988). To illustrate this point further one may reconsider the prediction of the cognitive permeation hypothesis of sensorimotor functioning in old age (Lindenberger et al., 2000). The cognitive permeation hypothesis states that the strength of the involvement of cognition in sensorimotor performance depends on status of the sensorimotor system. Aging-related changes in sensorimotor functioning can occur on multiple levels and can stem from a multitude of sources (e.g., Woollacott, 2000). It is unlikely that these changes do not differ in terms of strength or time of onset between individuals even within a restricted age range. From the perspective of the cognitive permeation hypothesis it is, therefore, relatively unrealistic to expect that the strength of intraindividual interrelations of sensorimotor and cognitive functions is invariant across individuals.

From the more general level of a lifespan perspective, it was of particular interest to explore empirically the range of interindividual differences in the intraindividual couplings between both domains of functioning. According to lifespan theory, person specific patterns of change are the basic unit of analysis that have to be understood first in terms of their antecedents, correlates, and consequences to allow the investigation of interindividual differences among them (Baltes et al., 1988). Up to the present, the empirical evidence that the findings obtained in the analyses of between-person differences generalize to the level of the individual is very sparse. To evaluate the validity of within-person process explanations of a stronger interrelationship between sensorimotor and cognitive functions associated with aging, within-person research designs are necessary. This particular approach was pursued in this dissertation.

3. Hypotheses

Although much is known about processing fluctuations in the context of aging a number of blind spots have remained. Thus far, research primarily focused on age differences in processing fluctuations on short time scales. Although some studies investigated processing fluctuations in cognitive performance occurring from day to day (e.g., Rabbitt et al., 2001), processing fluctuations on longer time scales have been largely ignored in the postural control domain. This lack of empirical investigation is surprising if one bears in mind that the regulation of processing fluctuations in postural control is highly important for an independent living in old age and if one considers the high incidence of falls in the elderly population (e.g., Lord et al., 1993). This dissertation aimed to further the understanding of age differences in postural control by investigating processing fluctuations on longer time scales (i.e., trial-to-trial and day-to-day). Furthermore, the relationship between processing fluctuations in postural control and attentional control were investigated in order to gain insights into possible sources of age differences in processing fluctuations.

3.1 Age Differences in Processing Fluctuations in Postural Control

This dissertation proceeded on the basis of the following assumptions. Processing fluctuations are the consequence of perturbations to a system that may stem either from within the system or from the environment. Furthermore, perturbations can occur on various time scales and perturbations on different time scales can have different sources. Thus, processing fluctuations in postural control can occur from moment to moment, from trial to trial, and from day to day. Moment-to-moment fluctuations indicate the online capacity to minimize body sway. Trial-to-trial fluctuations serve as an indicator for the ability to sustain control across repeated measurements. Day-to-day fluctuations indicate the robustness of the postural control system in the face of day-to-day changes in external and internal influential factors (e.g., variable cognitive functioning). Since the postural control system of older adults is more vulnerable to perturbations than that of younger adults, age differences were expected at all levels of analysis. With respect to age differences in processing fluctuations, three hypotheses were tested:

1. *Older adults have higher levels of moment-to-moment processing fluctuations in postural control than young adults.*
2. *Older adults have higher levels of trial-to-trial processing fluctuations in postural control than young adults.*
3. *Older adults have higher levels of day-to-day processing fluctuations in postural control than young adults.*

3.2 Sex Differences in Processing Fluctuations in Postural Control

The empirical evidence regarding sex differences in postural control is rather heterogeneous. There is, however, a general tendency indicating that women have better postural control than men in unperturbed standing. One theoretical explanation of this tendency has focused on the height difference between the sexes. In this perspective, women have superior postural control than men because their center of gravity is closer to their base of support. Another explanation hypothesized that the postural control system of men requires visual processing more strongly than that of women. The first perspective emphasizes a simple morphological cause, whereas the second proposes a mechanism that implies sex differences in the central control of upright stance. In this dissertation, sex differences in processing fluctuations in postural control were investigated on three different time scales. If sex differences in unperturbed standing were attributable to morphological differences, significant sex differences should only be apparent on the moment-to-moment level. If the female benefit in unperturbed postural control is partly a consequence of sex differences in central processing subcomponents of the postural control system, sex differences could result as a consequence of differences in general system robustness. In this case, sex differences should be observable on the level of trial-to-trial and day-to-day processing fluctuations. With respect to sex differences in postural control, this dissertation work investigated the following three hypotheses:

4. *Men have higher levels of moment-to-moment processing fluctuations in postural control than women.*
5. *Men have higher levels of trial-to-trial processing fluctuations in postural control than women.*
6. *Men have higher levels of day-to-day processing fluctuations in postural control than women.*

3.3 Processing Fluctuations in Postural Control: Cross-Domain Couplings

Recent theoretical approaches emphasize the involvement of cognitive functions in postural control (e.g., Massion, 1998; Shumway-Cook & Woollacott, 2000). Moreover, two different theoretical perspectives predict a strengthening of the relation between processing fluctuations in postural control and cognition associated with aging. The cognitive permeation view suggests that the postural control in older adults requires attentional control to be efficient (e.g., Krampe & Baltes, 2003; Lindenberger et al., 2000). The common cause account implies that a third factor like the efficiency of neuromodulation leads to an increasing dependency between both domains with advancing age (e.g., Baltes & Lindenberger, 1997). Both views are not mutually exclusive. Processes that strongly involve attentional control fluctuate in efficacy over time even in young adults (e.g., Braver et al., 2003). Aging-related declines in neuromodulation might lead to even noisier control processes (e.g., Braver et al., 2001; S.-C. Li, Lindenberger et al., 2001). Therefore, older adults face a specific dilemma. On the one hand, they are in greater need of attention to restrain processing fluctuations in postural control than young adults. On the other hand, their attentional control is less robust than that of young adults. These cross-domain and cross-level interactions could result in a stronger relationship between sensorimotor and cognitive processing fluctuations in older adults in comparison to younger adults. The correlational evidence indicating a stronger relationship between sensorimotor and cognitive functions associated with aging is primarily based on between-person variability. In contrast, the theoretical background explaining these findings focuses on intraindividual processes. The untested generalization from between-person differences to within-person processes is problematic (e.g., Molenaar et al., 2003). Therefore, this dissertation investigated cross-domain associations at the level of the individual. It was asked whether day-to-day processing fluctuations in postural control covary within individuals with day-to-day processing fluctuations in spatial working memory. Such a within-person relationship across time can be labeled intraindividual coupling. Based on the cognitive permeation hypothesis and common factor accounts it was hypothesized that older adults would show a stronger coupling than young adults. Furthermore, sex differences in the cross-domain couplings were investigated in addition to age differences. Empirical findings demonstrating a stronger dependency of visual information processing for effective postural control in men in contrast to women point to sex differences in central processes of postural control. If so, it might be the case that men are also more in need of attentional control of their postural control performance than women. Specifically, three hypothesis were formulated with respect to intraindividual couplings between sensorimotor and cognitive functioning:

7. *Daily processing fluctuations in postural control and spatial working memory are positively coupled at the level of individuals.*
8. *Daily processing fluctuations in postural control and spatial working memory are more strongly positively coupled among older adults than among young adults.*
9. *Daily processing fluctuations in postural control and spatial working memory are more strongly positively coupled in women than in men.*