6. DISCUSSION

This section discusses the findings of the present study. The first three parts refer to the three hypotheses of the study, and offer interpretations for the observed data patterns. Section 6.4 discusses some findings that were not part of the hypotheses, namely why children did not show higher overall dual-task costs than the young adults, and why the dual-task costs did not differ between 9- and 11-year olds. Following that, a possible interpretation of the three-way-interaction of task domain, balance difficulty, and cognitive task is discussed, and a potential explanation for the gender effect in single-task balance performance is offered. The discussion section finally presents a conclusion and an outlook on possible directions for future research.

6.1. Age Differences in Dual-Task Performance Trade-Offs

As predicted by the first hypothesis, children showed a clear performance trade-off between the two task domains in the dual-task situation, with smaller dual-task costs in the balance task as opposed to the cognitive task. Young adults did not show a trade-off pattern, and their dual-task costs were comparably high in both domains. The underlying reason for this trade-off was expected to lie in the characteristics of the sensorimotor task: Since the body's equilibrium was challenged when balancing on the ankle-disc board, and a rather demanding dual-task situation forced people to share their resources between two tasks, children prioritized the sensorimotor domain to preserve a sufficiently large safety region for controlling their postural stability. In the present study, children even demonstrated negative dual-task costs in the balance domain, which means that they improved their balance performance in the dual- as opposed to the single-task situation. Young adults, on the other hand, were able to deal with some performance decrements in the sensorimotor domain, and often showed dual-task costs in cognition and balance.

One interpretation for this finding is that younger adults have a larger safety region to start with, and their better developed control mechanisms enable them to flexibly exploit that region. As pointed out by Carpenter, Frank, and Silcher (1999), perceived threat to one's safety in balancing tasks can result in fear of falling. Participants in their study exerted tighter control on their centre of mass by increasing the stiffness in their ankle joints when standing on a high surface.

How challenged were peple when balancing on the board in the current study? In other words, how close did individuals get to the limits of their stability? Within the initial screening session, a measure of sway tolerance has been assessed, the so-called “Functional Stability Boundary” (FSB; see also Slobounov, Moss, Slobounova, & Newell, 1998; more details in Appendix L). The measure represents the size of the area that a participant can use for balance tasks without loosing the body’s equilibrium. The three age groups did not differ significantly concerning the size of that area. However, it has to be kept in mind that the FSB area is assessed while standing on the platform without the ankle-disc board. It is conceivable that standing on the board reduces the range of motion considerably, simply because the base of support is smaller, and the edge of the board starts touching the ground when leaning very far into a specific direction. To find out how large the COP area can possibly get on the board, I conducted several trials in which the edge of the board was constantly touching the ground, in all possible directions. The resulting mean COP area was about 50.000 mm^2, which is even larger than the average values for the FSB.

Table L.1 in Appendix L presents the average FSB values for each age group along with the average percentage of each individual’s FSB area used when balancing on the board under different single-task conditions. Balance performance on the board “uses” between 0.5 and 10 % of the individual’s maximum base of support, and children used a significantly larger proportion of their base of support than adults. Throughout the entire study, there were no instances in which participants actually stepped off the board during a balance trial. Nevertheless, prioritization of balancing performance in the children might have been influenced by the perception of increased insecurity and instability during more extreme movements, especially when they were already closer to their stability boundaries than young adults.

Does the percentage of FSB used in a certain balance single-task condition predict whether individuals prioritize the balance domain in a dual-task situation? The assumption would be that people who are already closer to their stability boundaries in the single-task condition will focus more strongly on the balance domain in the dual-task condition and will avoid further performance decrements, in order to preserve a sufficiently large safety region for controlling their postural stability. Balance was assessed under different conditions, that is, on the stable or moving platform and with different secondary tasks (reading numbers or listening to animal voices). It was not possible to simply average the COP areas of different conditions because performances differed significantly. Therefore, four correlation coefficients were obtained. The aggregated balance dual-task costs correlated (a) with $r = -.28$

($p = .161$) with the proportion of FSB used on the stable platform while reading numbers, (b) with $r = -.46$ ($p = .019$) with the FSB proportion used on the stable platform while listening to animal voices, (c) with $r = -.26$ ($p = .192$) with the FSB proportion used on the moving platform while reading numbers, and (d) with $r = -.48$ ($p = .012$) with the FSB proportion used on the moving platform while listening to animal voices. Although not all of these coefficients reached significance, all four correlations were negative. That indicates that participants who were using a larger proportion of their base of support in the single-task condition tended to show smaller dual-task costs in the balance domain. Preserving a sufficiently large safety region in the balance task can therefore be one reason for the task prioritization seen in children.

The following section discusses some alternative factors that might have influenced the data pattern, like balance task difficulty or age differences in the strategies used.

6.1.1 Factors Potentially Influencing the Data Pattern

Balance task difficulty. It has been shown above that children were operating closer to their stability boundaries than young adults when balancing on the board. Children also had significantly larger COP areas than adults in each balance condition. The balance task can therefore be considered more difficult for children than for adults, forcing them to invest more of their resources into its' execution already under single-task conditions. Young adults, on the other hand, might have experienced the balance task as rather easy. When the single-task balance performances were correlated with the aggregated balance DTCs, the following pattern emerged: Balance DTCs correlated (a) with balance performance on the stable platform while reading numbers with $r = -.43$, $p < .05$, (b) with balance performance on the stable platform while listening to animal voices with $r = -.62$, $p < .01$, (c) with balance performance on the moving platform while reading numbers with $r = -.43$, $p < .05$, and (d) with balance performance on the moving platform while listening to animal voices with $r = -.74$, $p < .001$. The pattern is very consistent: All four correlations were significant and negative, indicating that participants with larger COP areas showed smaller balance DTCs. It can be concluded that individually perceived difficulty of the balance task has an influence on the pattern of sensorimotor DTCs. Participants who showed a lot of sway under single-task conditions also showed a tendency to prioritize the balance task in a dual-task situation, and to keep up or even improve their balance performance when resources were taxed.

Potential for improvement larger in children's balancing. Another aspect about the balance task might be that children not only perceive the balance task as more difficult than adults, but also as a task that can be influenced more efficiently than the cognitive task. The difficulty of the cognitive task has been adjusted to each individual's performance, leading to stable performance levels that do not approach the ceiling, and rendering pronounced performance gains over the course of the dual-task phase unlikely. Young adults might have similar experiences with the balance task, because their performance on the ankle-disc board is better and less variable than children's performance. Young adults might therefore divide their attention equally between the two tasks in a dual-task situation, because they perceive it equally likely for both task domains that resource investment actually "pays off" in terms of performance improvement. Children, on the other hand, experience more pronounced changes in performance in the balance task, also because their performance in the sensorimotor domain tends to be more variable than in young adults (Deutsch & Newell, 2004). They might therefore think that performance in the balance task is easier to improve than performance in the cognitive task, and that might motivate them to focus more on the balance task in a dual-task situation.

A general question remains with this line of reasoning: Does the prioritization of one task domain over the other require a conscious decision process or not? There are indications from previous research that people's retrospective reports about which task they have been focusing on in a dual-task situation do not correspond well to their actual performance trade-off patterns. For example, unpublished data from the study by K.Z.H. Li et al. (2001) show that the vast majority of participants reported to have been focusing more strongly on the cognitive task of memorizing while concurrently walking on the track. However, the data pattern of older adults indicates that they prioritized the sensorimotor domain. In the present study, participants were asked at the end of the dual-task phase which task they had been focusing on. Most participants reported to have focused almost exclusively on the cognitive task, and not having invested any attentional capacity into the balance task. There were no age differences concerning these retrospective reports (see Gronostaj, 2004, for details). This indicates that people do not have to make a conscious decision about their resource allocation processes, but can nevertheless show pronounced trade-off patterns in their performances.

Age differences in strategies for single-task balancing. Obviously, different strategies can influence the behavior in dual-task situations even when people are not able to report on them. The strategy that appears in the data pattern of the dual-task phase of the present study is one of sensorimotor task prioritization in children, and of equal task emphasis in young adults. However, behavior in the single-task situation can also be influenced by strategies, for example if children approach the balance task in a rather "playful" way, and do not follow the instruction to achieve a small COP area, maybe because they are bored. In the dual-task situation, when attentional resources are focused on the cognitive task, children might refrain from "playing", because they are so busy performing the cognitive task. However, children's apparent motivation to perform well in balancing also under single-task conditions, and the fact that single-task balancing also included the performance of a simple secondary task renders this assumption unlikely.

Automatization of the sensorimotor task. Does balance performance improve under dual-task conditions simply because it has become automatized? Well-practiced performance in sensorimotor task often starts deteriorating when attention is focused on its' performance (Beilock, Carr, MacMahon, & Starkes, 2002; Beilock, Wierenga, & Carr, 2002). Swan, Otani, Loubert, Sheffert, and Dunbar (2004) had younger and older subjects perform a spatial or non-spatial memory task while holding as still as possible on a force platform. They found that both the spatial and non-spatial memory task improved balance for older adults under the most difficult balance condition. In a study by Maylor and Wing (1996), cognitive load led to decreases in sway in a young-old group (mean age 57 years), and to increases in sway in the older participants (mean age 77 years). However, even if automatization was a crucial point to explain the findings of the current study, it remains unclear why young adults do not show performance improvements in balancing under dual-task conditions. There is no reason to assume that children automatize a sensorimotor skill, but young adults do not.

Does less sway really represent a "better" balance performance? In the present study, balance performance was measured with the COP area, and people were always instructed to try to keep that area as small as possible. It was assumed that successfully reducing one's body sway is an indication for an improvement of balance performance. However, one could also argue that successful balance performance is rather represented by a system that can tolerate sway, and that is able to perform a variety of movements and to react flexibly to a large range of balance conditions without loosing the body's equilibrium. Many studies on posture control instruct participants to "stand as still as possible". At first sight, this is a rather artificial task, because everyday postural control usually does not require to reduce body sway to a minimum, but instead to move the body through space in a secure and well-coordinated way (for critiques of the "quiet stance" paradigm in postural assessment, see Patla, Frank, & Winter, 1992; Riley, Stoffregen, Grocki, & Turvey, 1999; Stoffregen, Smart, Bardy, & Pagulayan, 1999).

Concerning motor development, Hay and Redon (1999) found evidence for a temporary overcontrol of posture in 6- to 8-year olds. The authors speculate that children's limits to tolerate imbalance increase while they grow up. Kirshenbaum, Riach, and Starkes (2001) present longitudinal data that further support the nonlinearity of postural control development in 5- to 8-year olds using a quiet stance paradigm. In this line of research, developmental stages in which children reduce their body sway do not represent improvements in balancing abilities, but rather indicate that the developing system has not settled on a new, efficient solution to a specific motor problem yet. In a demanding situation, the balance system is therefore operating at its limits and cannot “afford” movements any longer.

6.1.2. Summary Concerning the Trade-Off Pattern

In the present study, children showed a trade-off between cognitive and sensorimotor dual-task costs in favor of the balance domain, while young adults had equal dual-task costs in both domains, as had been predicted by the first hypothesis. There is evidence that children prioritized the sensorimotor domain because they were operating closer to their stability boundaries. This view is further supported by the negative correlation of COP areas and balance DTCs: Individuals who swayed more in the single-task condition tended to prioritize their balance performance in dual-task situations. This prioritization does not have to be based on a conscious decision, and the system might automatically shift resources to the task of keeping the body’s equilibrium in taxing situations.

It is unlikely that the trade-off pattern simply emerged because children used maladaptive strategies for single-task balancing, or because they perceived the balance task as being easier to influence than the cognitive task. Self-report data showed that participants from all age groups claim to have focused more strongly on the cognitive task in the dual-task situation. However, the fundamental question whether the “quiet stance” paradigm is a useful way to measure balance performance remains. It might be more ecologically valid to measure balance with the instruction to move as much as possible without falling in future studies.

The following section discusses why the performance trade-off pattern was not influenced by the difficulty of the sensorimotor task, which had been expected according to the second hypothesis.

6.2 Dual-Task Costs And Sensorimotor Difficulty

Different difficulty levels were used for the balance task of the present study. Participants were either balancing on the stable platform or on a continuously moving platform. It was assumed that balancing on the moving platform would be more difficult than balancing on the stable platform, and would force participants to invest more of their resources into the task. Furthermore, balancing on the moving platform required that a larger part of the base of support was used in order to counteract the externally generated movements, forcing participants to operate closer to their stability boundaries. The second hypothesis therefore assumed that children would prioritize the balance domain even more than on the stable platform, by showing a more pronounced difference between cognitive and sensorimotor performance. However, the data pattern of the present study did not support this hypothesis. In all three age groups, the dual-task costs did not differ by balance difficulty, and the trade-off between the two tasks in the children was comparable for the stable and the moving platform condition. This data pattern renders certain assumptions of different resource theories more or less likely, and these are discussed in the following section.

Implications for resource theories. One basic assumption in resource theories is that a more difficult task requires more resources or mental capacity for its' execution (Guttentag, 1989a; Wickens, 1984, 1991). Some resource theories on dual-task performance further assume that the two tasks compete for resources from a unique, general-purpose unit or structure (Kahneman, 1973). Therefore, when performing a difficult task along with another task in a dual-task situation, performance decrements are expected to be more pronounced than when an easier task is used. The pattern of dual-task costs found in the present study does not lend empirical support to this assumption, because increases in the difficulty of the balance task did not lead to higher overall dual-task costs in the dual-task situation. Furthermore, the trade-off between the task domains did not get more pronounced.

An alternative theoretical account of the concept of resources questions the existence of a general purpose unit or structure, and proposes a pool of different and distinguishable resources instead, some of which are used by one task, some by the other, and some by both tasks in a dual-task situation (Navon & Gopher, 1979). The degree to which specific processing resources are used by both tasks would then predict the amount of interference between them. According to the literature, processing resources can differ by (a) modalities of stimulus input (visual vs. auditory), (b) internal representation codes (e.g., visual vs. verbal), (c) response modes (manual vs. verbal), and (d) cerebral hemispheres (Friedman, Polson, Dafoe, & Gaskill, 1982; Hiscock & Kinsbourne, 1978). Under these assumptions, the difficulty of the balance task might not influence the overall dual-task costs if the processing resources that are needed to deal with the more difficult balancing task are not relevant for the concurrent cognitive task.

The balance system is rather complex and requires a variety of different processing resources. Balancing requires input from the vestibular, visual, and somatosensory system, and this input has to be integrated by the central nervous system (e.g., Birbaumer & Schmidt, 1999). The body's motor system triggers body movements that are necessary to react to disturbances of the body's equilibrium. The crucial point for the present study is whether balancing also requires considerable amounts of cognitive resources, like for example working memory capacity or attentional control, and whether the amount of cognitive resources needed is increased when balancing on a moving instead of a stable surface. The fact that the pattern of dual-task costs did not change with increasing balance difficulty suggests that this is not the case.

Concerning the relation of the present findings to resource theories, another possibility is that people are able to activate additional resources under dual-task conditions when the situation becomes more demanding. If additional resources can be activated, an increase in the difficulty of a task does necessarily lead to performance decrements. Lindenberger, Scherer, and Baltes (2001) conducted a study in which cognitive tasks were administered to middle-aged adults under age-simulation conditions of reduced visual acuity, reduced auditory acuity, or both. Participants under these conditions did not deviate negatively in their intellectual performance from participants without such simulated losses. Individuals in groups with effective or placebo reductions of sensory acuity sometimes even showed a tendency to perform above the level of the no-treatment control-group. As a post-hoc explanation, the authors refer to Düker's (1963) concept of an increase in attention and effort (*reaktive Anpassungssteigerung*), which assumes that individuals invest more effort under conditions of reduced sensory acuity to compensate for a supposedly challenging experimental condition. Although this pattern of findings had occurred between subjects, and no direct comparison of each individual's performance with and without acuity reductions has taken place, the results nevertheless point to the possibility of a recruitment of additional resources in demanding situations.

However, this possibility causes problems to resource theories in general, because one underlying assumption is that participants are always motivated to perform as well as possible on a task. Wickens (1984) describes the construction of *performance-resource functions* (PRF), which relate the quality of performance to the quantity of resources invested in a task. One assumption is that maximum single-task performance occurs when all resources are invested in the task. However, in some tasks there is a limit to performance improvement (e.g., when the task is rather easy, reaching 100 % correct can be achieved without investing the maximum amount of resources into the task, and performance will not improve further even if more resources are invested). Performance in such a situation is said to be *data limited*. On the other hand, in the performance range in which performance still changes with added or depleted resources, performance is said to be *resource limited.* Figure 29 shows a hypothetical performance-resource function (PRF), adapted from Wickens (1984).

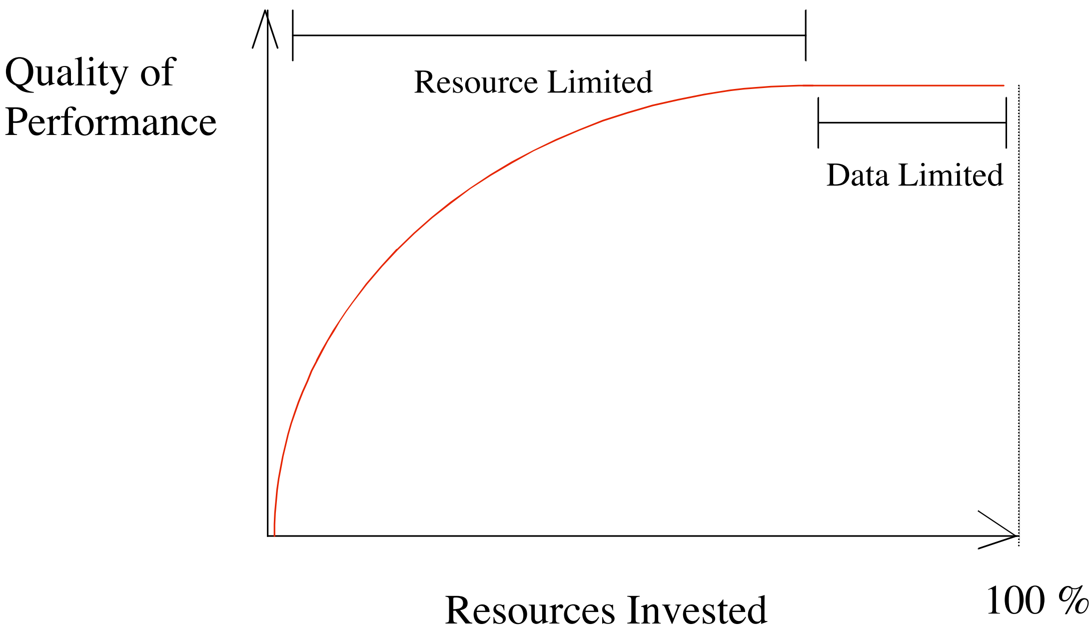

Figure 29. Hypothetical Performance-Resource Function: Resource- Versus Data-Driven Constraints

Note. The function depicts the performance under single-task conditions depending on resource investment. The figure is adapted from Wickens (1984).

Plotting theses PRFs crucially depends on the assumption that subjects do invest a certain amount of resources into a task when asked to do so. This is problematic, since the definition of “effort” might differ across individuals, and they might not be able to actually exert control over their resource allocation in a very fine-graded manner. More fundamentally, the assumption that increases in task difficulty might lead to a higher overall level of available resources really causes problems to resource theories. It would not be possible to depict performance in relation to resource investment when the amount of available resources can change depending on the characteristics of the task. The data pattern of the present study can therefore only be interpreted within the resource framework if multiple and independent resource pools are assumed.

However, a closer inspection of what “task difficulty” really means in the balance domain maybe also helps to understand the data pattern. The next section will therefore discuss the assumption of balance task difficulty in some more detail, and also relate the balance task to theories of motor control.

Motor control theories and balance task difficulty. What exactly were the differences between the two balance difficulty conditions? On the moving platform, specific body movements counteracting the forces of the platform were necessary to stabilize oneself on the ankle-disc board. Movements of the platform always occurred on the lateral plane. Participants had to counteract this perturbation of their balance by shifting their weight more to their left or right foot, opposite to the direction into which the platform was tilting at a given moment. Stabilization of the body's equilibrium on the stable platform required less extreme movements, because no reaction to perturbing events was necessary. The task was rather to balance on the board while using only a small proportion of the base of support, and by using only moderate and well-coordinated body movements in order to achieve a small COP area.

It can be speculated that the balance control processes necessary in these two conditions differ. Hay and Redon (1999) distinguish between feedforward and feedback control of balance. *Feedforward control* comes into play when own movements generate balance disturbances, and "anticipatory" postural adjustments can be triggered prior to the self-induced disturbance. Since sway on the ankle-disc board on the stable platform is purely self-generated, participants have the chance to counteract the sway not only by reacting to it as soon as they perceive the movement (feedback control), but also in an anticipatory fashion using feedforward control. *Feedback control*, on the other hand, is relevant when movements are externally triggered and unpredictable, and require a reaction of the body. On the moving platform, the surface is tilting, such that participants are forced to react to these externally generated movements. On the other hand, feedforward control might also play a role, because the movement of the platform is continuous, and therefore predictable. In sum, balancing on the ankle-disc board probably always requires both kinds of control processes, although the stable platform might be dominated more strongly by feedforward control.

Theories on feedforward and feedback control of motor behavior do not deal with the question whether balance control also requires cognitive resources. It can only be speculated that cognitive control processes are more important for feedforward control, since these require a plan about the future state of the system for successful anticipatory movement regulation. Feedback control, on the other hand, might be more reflex-like and might not require a strong cortical involvement. One indication for that is also the developmental pattern of these processes (Hay & Redon, 1999). Feedforward control becomes more efficient with increasing age in childhood, while feedback control operates efficiently from an early age on, showing little developmental changes during childhood. What are the implications for the present study? If feedforward control is more important on the stable platform, and also more cognitively demanding, it might be unreasonable to believe that balancing on the moving platform is “more difficult”. Although it does lead to larger COP areas, it might in fact need fewer (or maybe just as many) cognitive resources to be performed successfully, and it therefore does not interfere with the concurrent cognitive task more strongly than balancing on the stable platform.

Summary. The data pattern of the present study did not support the second hypothesis. Contrary to the prediction, the trade-off pattern between cognitive and balance dual-task costs was not influenced by balance task difficulty, and children did not show a more pronounced trade-off pattern on the moving as opposed to the stable platform. This pattern contradicts the assumption of a single, unitary pool of resources that has to be accessed by both tasks, because if one of the tasks is more difficult, it should require more of the shared processing resources, and should therefore cause larger performance decrements in a dual-task situation. A resource framework that suggests a pool of multiple independent resources could only account for the current data if the increase in balance task difficulty does not influence its need for *cognitive* resources. The current data do not preclude the possibility that the increase in task demands led to an overall increase in available resources, which then enabled participants to keep their performances on the same level as with the easier balance task. However, such an explanation fundamentally questions the basic assumptions of resource accounts, namely that the overall availability of resources does not change depending on task demands. Finally, the theory of feedforward and feedback control in motor behavior might be helpful in distinguishing the processes that are required when balancing on the stable or on the moving platform. It can be speculated that the need for cognitive resources is indeed not necessarily larger when balancing on the moving platform than when balancing on the stable platform.

The next section discusses the findings concerning the third hypothesis, namely whether children were not able to de-emphasize the sensorimotor domain, even when instructed to focus more strongly on the cognitive task. Young adults were expected to be able to flexibly shift their attention according to instruction in a differential-emphasis condition.

6.3 Resource Allocation Under Differential-Emphasis Instructions

In the last session of the study, participants performed the dual tasks under different emphasis instructions. In some instances, they were told to focus more strongly on the cognitive domain, and in other instances, to focus more strongly on the balance domain. Participants were reinforced for successful performance, by collecting points that could later on be traded into sweets. This might have led to the rather high overall performance level observed in that session, with many instances of dual-task costs that were not distinguishable from zero or even significantly below zero, indicating that participants were able to improve their performance in the dual-task situation compared to the single-task situation.

However, in order to investigate whether participants managed to shift their attention according to instruction, the dual-task costs of the two domains (balance vs. cognition) within each emphasis-condition were compared. The performance pattern partly confirmed the hypothesis: Children always showed lower dual-task costs in the balance domain as opposed to the cognitive domain, independent of emphasis condition. That is, even when they were instructed to focus more strongly on the N-back task, their balance dual-task costs were negative and reliably lower than their cognitive dual-task costs. This was interpreted as an indication for loss-based selection of the balance domain. However, contrary to the hypothesis, young adults did not show a flexible resource allocation in their dual-task costs: Their balance and cognitive dual-task costs did not differ under the two emphasis-instructions.

Another level of investigating the ability to shift resources according to instruction was to analyze the distribution of reinforcement points. Performance criteria have been calculated by taking the dual-task performance of a previous session into account. All age groups were able to collect more points in the task domain that they should focus on than in the alternative task domain. This indicates that young adults were not clearly superior to the two children's groups in adjusting their performance according to differential-emphasis instructions.

Do negative balance DTCs in children really show that children's prioritization of the sensorimotor domain is due to loss-based selection? It was argued initially that the differential-emphasis instruction should allow for a distinction between the processes of elective and loss-based selection underlying the trade-off pattern in children's dual-task performances. It was assumed that loss-based selection is the underlying process if children would not succeed in shifting their attention away from the balance task. In their dual-task costs, children actually showed no change in their fundamental prioritization of balance performance, even when they were instructed to focus more strongly on the cognitive task.

However, it has to be kept in mind that over and above the instruction to "focus more on the cognitive task", participants were actually given clear performance aims for each task domain, namely by being informed about a certain performance level that they should try to reach in each task. The reinforcement scheme mirrored the differential-emphasis instructions, by rewarding participants with more points when they reached the performance aim of the emphasized task than when they reached the aim of the other task.

According to Figure 28, the distribution of reinforcement points did not show a clear preference for the balance domain in children, because they did not collect significantly more points for achieving the balance aim than for achieving the cognitive aim. However, the performance range in the balance task in which points could be collected at all was already considerably better than the balance performance under single-task conditions. The crucial point is that the need to preserve a sufficiently large safety region has already been satisfied under these circumstances. The general prioritization of balance in children was consistent, it differed from the pattern of young adults, and it also occurred in the differential-emphasis phase. However, that it remains unclear if children would be able to sway *more* when instructed to do so, while concurrently performing better in the cognitive task. The results of the current study suggest that children would not be able to follow theses instructions.

The data pattern of the differential-emphasis phase helps to clarify another issue about dual-task performance improvements in balance. As argued above, it is possible that balance is a well-practiced sensorimotor skill, and that performance in that skill starts deteriorating when attention is focused on its' performance. Studies have shown that this is the case for skills like golf putting or ball dribbling (Beilock, Carr, MacMahon, & Starkes, 2002; Beilock, Wierenga, & Carr, 2002). Over and above the difficulty of explaining why balance of the present study only improves in children, but not in adults under dual-task situations, the data pattern of the dual-task phase shows that balance in all three age groups can actually be improved when the instruction is to focus on the balance task. This clearly speaks against the possibility that balance on the ankle-disc board belongs to the well-practiced sensorimotor skills whose performance is harmed when deliberately attending to it.

Summary. The data pattern of the differential-emphasis phase lends further support to the assumption that children's prioritization of the balance domain is caused by processes of loss-based selection. Children always showed significant negative dual-task costs and therefore performance improvements in the balance domain, even when they were instructed to focus more strongly on the cognitive task. The pattern of dual-task costs in young adults did not indicate that they allocate their resources flexibly according to instruction. However, when considering the distribution of reinforcement points for each task domain and emphasis instruction, all three age groups showed some tendencies to follow the differential-emphasis instructions, by collecting more points in the domain they should focus on than in the other domain. The data further rule out that the balance task of this study belongs to the sensorimotor skills whose performance suffers when attention is payed to their execution.

6.4. Additional Findings Warranting Discussion

The following sections refer to some empirical findings of the present study that were not included in the hypotheses but nevertheless warrant discussion.

6.4.1 Children Do Not Show Higher Overall Dual-Task Costs Than Adults

According to the resource framework, a dual-task situation requires that limited resources are shared between two tasks. There are different theoretical assumptions about the concept of resources. Limited resources can either stem from a single, unitary unit or structure (Kahneman, 1973), or from a pool of independent resources, some of which are needed for both tasks (Naphon & Gopher, 1979; see also Guttentag, 1989a, or Wickens, 1984, 1991). Dual-task interference results if the tasks compete for the same resources. Concerning age differences, one possible assumption is that the total supply of resources does not vary with age, but different tasks need fewer resources with increasing age (Case, 1985). Young children have often shown higher dual-task costs if working on the same task combinations as adults or older children (Guttentag, 1989a; Huang & Mercer, 2001). However, when participants were equated on task difficulty of the single-task, either by training (Birch, 1978) or by manipulating task presentation parameters, such that every participant performed at the same level (Irwin-Chase & Burns, 2000; Whitall, 1991), dual-task costs did not differ any more between different age groups.

In the present study, participants were trained on each component task, and task difficulty of the cognitive tasks was manipulated individually. It is therefore consistent with the studies by Birch (1978) and Irwin-Chase and Burns (2000) that children and young adults did not differ in their cognitive dual-task costs. However, since a dual-task situation forces people to share their resources between two concurrent tasks, it is also important to consider the overall dual-task costs, which emerge when the dual-task costs of the two domains are averaged. In the present study, there were no age differences between children and young adults and between 9-year olds and 11-year olds in overall dual-task costs (averaged over task modality, type of cognitive task, and balance difficulty). This pattern indicates that children did not suffer disproportionately from the dual-task manipulation in the study, and that the differences between children and adults lied in the trade-off pattern between the two task domains – occurring in children, but not in adults – and not in overall levels of dual-task costs.

These results differ from the performance pattern found in another study conducted in our lab, in which children and adults were walking on a narrow track while concurrently performing a semantic word fluency task (Krampe, Schäfer, & Baltes, in preparation). The overall dual-task costs of that study were higher for 9-year olds than for 11-year olds. The following section will discuss potential explanations for the differences in dual-task patterns between the two studies.

6.4.2 Nine-Year Olds Do Not Differ From Eleven-Year Olds in Their Dual-Task Costs

In the present study, 11-year old children were superior to 9-year olds in almost all single-task performances. They remembered significantly more words in the MOL task and demonstrated consistently smaller COP areas on the ankle-disc board. They also showed superior performance in the N-back task, although these differences did not always reach significance. The difficulty manipulation of the two cognitive tasks successfully equated the two children's groups on their cognitive performances measured in percent correct. Concerning the performance reduction from single- to dual-task, 9- and 11-year olds did not differ in their proportional dual-task costs, and both groups showed the same trade-off pattern between balance and cognition.

This pattern differs from the pattern of dual-task costs of the "Walking and Word Fluency" study, which is described in Section 2.3.5. In that study, 9- and 11-year old children and young adults were walking on a narrow track while concurrently naming items for a word fluency task. In the single-task conditions of that study, adults walked faster and named more fluency items than 11-year olds, and 11-year were superior to 9-year olds in these performances. Concerning the proportional dual-task costs, which are depicted in Figure 5, all three age groups showed dual-task costs in the walking domain. However, only the 9-year olds showed a consistent performance decrement in the fluency domain when concurrently walking on the track. Eleven-year olds and young adults were able to name as many fluency items as under single-task conditions. This pattern can be interpreted as a prioritization of the cognitive domain by the two older groups. Nine-year olds did not show any differences between the dual-task costs of the two domains, and they showed higher overall dual-task costs than 11-year olds and young adults.

Summarizing these findings, the present study differed from the "Walking and Word Fluency" study concerning (a) age differences in overall dual-task costs, (b) age differences in the dual-task trade-off patterns, and (c) the direction of the prioritization of a specific task domain over the other. What might be the factors responsible for the differences between the two studies? The fact that age differences in overall dual-task costs occurred in the "Walking and Word Fluency" study, but not in the present study, can be explained with the manipulation of task difficulty. In the present study, the difficulty of the two cognitive tasks was adjusted for each individual, while task difficulties were not adjusted to age groups or individuals in the "Walking and Word Fluency" study. The fluency task might have been easier for older children and young adults, because these age groups use certain strategies like clustering more often (Kobasigawa, 1974) and have a larger knowledge base than 9-year olds (Bjorklund, 1987; Chi & Ceci, 1987).

The characteristics of the sensorimotor tasks might explain the differences in the dual-task trade-off patterns between the two studies. Although walking on the narrow track requires that participants pay attention to where they step, performance decrements might not be perceived as threatening. Under dual-task conditions, when fluency items have to be produced concurrently, it maybe was an adaptive strategy to sacrifice some of the walking performance by simply walking a bit slower. On the other hand, when neglecting the balance task in the current study, children would maybe risk sacrificing their body's equilibrium. They therefore focused on that task, which resulted in a dual-task trade-off pattern in favor of the sensorimotor domain.

The main result concerning the pattern of dual-task costs of the present study is that children showed smaller dual-task costs in the balance domain as opposed to the cognitive domain, while young adults did not show such a performance trade-off. However, the statistical analysis of dual-task costs also revealed a three-way interaction between task domain, balance difficulty, and cognitive task, which is discussed in the following section.

6.4.3 Towards Explaining the Three-Way-Interaction of Balance Difficulty, Cognitive Task, and Task Domain

The mixed-design ANOVA on the dual-task costs of the present study analyzed the within-subjects factors of task domain (balance versus cognition), cognitive task (MOL versus N-back), and balance difficulty (stable versus moving platform), and the between-subjects factor of age group (see Section 5.4.2 for details). In addition to other results, this analysis detected a significant three-way interaction of the within-subjects factors. This three-way interaction did not interact with the age contrasts comparing children to adults or with the age contrast comparing 9- to 11-year olds. The pattern of dual-task costs (see also Figure 20) indicated that balance difficulty had an effect on the cognitive dual-task costs, but only for the task combination of balance and N-back, and not for the task combination of balance and MOL. In other words, when balancing was performed concurrently with the N-back task, cognitive dual-task costs for the N-back task were higher on the moving than on the stable platform. On the other hand, when balancing was performed concurrently with the MOL task, cognitive dual-task costs in the MOL task did not differ between the stable and the moving platform.

What might have caused these differential effects of balance difficulty on the cognitive dual-task costs? It might be informative to take a closer look at the specific task constraints of each particular dual-task situation. When performing the MOL task while balancing, participants had to generate mental images after the presentation of each location-word pair. The stimuli pairs appeared in regular temporal intervals, whose length depended on the (individually adjusted) difficulty level of the task. However, the MOL task offered people a certain flexibility concerning which processing step had to be performed at which point in time. The important aspect of the task was that the generation of the image should have taken place before the next stimulus pair was presented. After each MOL trial, participants tried to recall as many items as possible.

When performing the N-back task while balancing, the digits presented on the screen had to be encoded and stored in short-term memory, in order to be able to verbalize them later at the correct serial position and at the correct time-point within the trial. N-back stimuli appeared in rather rapid succession, with inter-stimulus intervals varying between 1000 and 2020 ms, depending on each participant's performance level. The crucial point is that the time constraints of the N-back task were more restrictive, since the task required participants to name the digit at a specific point in time, namely when the second- (or fourth-) next digit appeared on the screen. The intervening processing steps of encoding and storing the successive digits had to be tightly synchronized to the rhythm of stimulus presentation.

When balancing on the moving platform, participants had to counteract the movements of the tilting platform. The movements of the platform were continuous, also requiring a synchronization of the body's movements to the regularly shifting platform. Therefore, when the N-back task had to be performed concurrently while balancing on the moving platform, participants had to deal with two different rhythms: the rhythm of stimulus presentation of the N-back task, and the rhythm of the tilting platform, which had to be counteracted by specific body movements. Since these factors had not been designed to follow the same temporal pattern in the present study, the two rhythms were asynchronous. Research on the tapping of polyrhythms, in which people have to tap two nonharmonically related rhythms with their hands, has shown that this is a very difficult task (Klapp, 1985; Peper, Beek, & van Wieringen, 1996; Summers, Rosenbaum, Burns, & Ford, 1993; Summers, Sargent, & Hawkins, 1984). It is therefore conceivable that participants were confused by the two different rhythms, and since they tended to focus on the balance task in situations in which the body's equilibrium was challenged, they "lost track" of the N-back more easily, resulting in higher cognitive dual-task costs as compared to the stable platform condition.

In sum, the two cognitive tasks implemented different temporal constraints on task performance, which might have interacted with balancing on the moving platform. The temporal constraints of the MOL task were not as strong as in the N-back task. When N-back was performed on the moving platform, participants were faced with the difficulty of combining two asynchronous rhythms, and this probably led to an increase in cognitive dual-task costs.

6.4.4 Possible Reasons for Gender Differences in Balance Performance

In the present study, females showed significantly less sway than males when balancing on the board, and this finding emerged on the stable and on the moving platform. The effect did not interact with age group (see Section 5.3.3 for details). This difference was not due to males being taller than females and therefore having a higher centre of pressure, because the effects remained when differences in body height were controlled for. However, there were no gender differences in the cognitive tasks or in the dual-task costs of any task domain, and there were also no gender differences in balancing without the ankle-disc board on the stable or moving platform during the screening session.

What might be the reason underlying this data pattern? Are similar results published in the literature? A meta analysis by Thomas and French (1985) investigated gender differences and age changes in a variety of motor tasks. They included 14 studies on balance in childhood, with more than 2000 female and more than 2000 male subjects. No gender differences for balance performance were detected until puberty. After the age of 10 to 13 years, male performance became better than female performance, with a performance advantage of 1 unit in weighted standard deviations at the age of 19. However, when averaging over the age range of 3 to 19, the performance advantage of males was reduced to

0.09 weighted standard deviations, which is a very small effect (Cohen, 1969). Other individual studies found no gender differences in balance performance in 3- to 6-year olds (Foudriat, Di Fabio, & Anderson, 1993), in first to third graders (Pissanos, Moore, & Reeve, 1983) or in 8- to 10-year olds (Figura, Cama, Capranica, Guidetti, & Pulejo, 1991). Consistent with the present study, several studies have reported girls to be superior to boys in balancing (Clark & Phillips,1987; De Oreo & Wade, 1971; Peeters, Breslau, Mol, & Caberg, 1984) or motor coordination (Kasa & Majherova, 1997). In a study by Plimpton and Regimbal (1992) with first graders, balance performance was influenced by an interaction of gender and race, with White girls balancing significantly better than African-American boys. Thus, the pattern in the literature seems to be rather inconsistent. It can be assumed that the balance tasks differ considerably from study to study, and the results might strongly depend on the type of task used to assess balance.

The body's dimensions also influence balance performance. Clark and Phillips (1987) state that a common explanation for females' superior or equivocal performance in static balance tasks is that the male center of gravity is higher above the base of support, although the differences are rather small in reality. Other anthropometric factors like foot breadth and foot length are larger for males and therefore do not explain gender differences in balancing favoring girls. However, the factor of hip width might play an important role in the present study. It can be speculated that skillfully shifting one's weight to the left or right foot, a movement that is necessary to counteract the movements of the platform, is easier for females, since their hips tend to be wider, giving them more flexibility in their range of reactions. Hip width does not only differ between adult males and females. Clark and Phillips (1987) point out that females in all age groups from 4 to 10 years exhibit greater hip widths than their male counterparts of the same age. However, this does not explain why the gender differences also occur on the stable platform, where movements are not so much constrained by the moving platform, and the centre of pressure can be shifted in any direction.

Woollacott and Shumway-Cook (1990) distinguish between the ankle strategy, the hip strategy, and the suspensory strategy (lowering the point of gravity) that can be used to maintain balance. It can be argued that the most efficient way to balance on the ankle disc-board is a combination of the ankle and hip strategies. Movements in the ankles definitely are very important to balance on the board, because they allow for immediate reactions to the movements of the board. Nevertheless, it might also be useful to counteract some of the "remaining" sway by using the hip strategy. I am not aware of research on gender differences in the use of these different balance strategies, but one might speculate that females are more efficient in using the hip strategy than males, due to biomechanical constraints, and therefore are more successful when balancing on the board.

6.5 Conclusions

The present study investigated how 9-year-old and 11-year-old children and young adults allocate resources when concurrently performing a cognitive and a sensorimotor task. Two different cognitive tasks were used, a working memory and an episodic memory task. The sensorimotor task consisted of balancing on an ankle-disc board. All tasks were trained extensively under single-task conditions, and task difficulty of the cognitive tasks was adjusted individually to each participant's performance level. Balancing was assessed with different difficulty levels, either on the stable or on the moving platform. The three age groups differed on their performance levels in all three tasks, with adults showing superior performance than children, and older children often outperforming younger children. The difficulty manipulation of the cognitive tasks successfully equated task performance of the three age groups, such that all participants scored about 80 % correct under single-task conditions. Proportional dual-task costs were calculated for each task, expressing performance decrements under dual-task conditions in percent of individual single-task performance.

Children showed a trade-off between their cognitive and sensorimotor dual-task costs, with higher dual-task costs in the cognitive domain than in the balance domain. Balance dual-task costs were even negative in the children, indicating that they improved their balance performance under dual-task as compared to single-task conditions. In the cognitive domain, performance was reduced in all age groups under dual-task conditions. Young adults did not show differential levels of dual-task costs between the two task domains. This pattern was interpreted as evidence for a selection process in the children's group: They prioritize the balance domain, because the dual-task situation is rather challenging, and they preserve a sufficiently large safety region for controlling their postural stability. Additional evidence for that interpretation stems from the observation that the balance task was more difficult for children than for adults already under single-task conditions, because they showed more sway and had to use a larger proportion of their base of support. In general, participants with larger COP areas under single-task conditions were more likely to show balance improvements in the dual-task situation. However, the fundamental question remains whether showing little sway on the ankle-disc board really represents successful balance performance. Maybe successful performance should rather be defined as being able to tolerate more sway without reaching one's stability boundaries.

Contrary to the predictions, there were no differences in the dual-task cost patterns between the stable and the moving platform, neither for children nor for adults. The discussion argues that this data pattern can only be explained by a resource account with multiple independent resources, some of which are used by one task, and some by the other. According to this account, interference only occurs if the two tasks compete for the same resources. Balancing on the moving platform in the current study might not have required more cognitive resources than balancing on the stable platform, such that the resulting pattern of dual-task costs did not differ between the two balance difficulty conditions.

In a session with differential-emphasis instructions, children kept on showing lower balance dual-task costs than cognitive dual-task costs, even when instructed to focus more on the cognitive task, supporting the assumption that children's prioritization of the balance domain is caused by processes of loss-based selection. Young adults did not show a clear pattern of flexible resource adjustment in their dual-task costs. The analysis of reinforcement points indicated that all three age groups collected more points in the task domain that they should focus on than in the alternative domain. However, the balance performance for which children received points was already in the range of negative dual-task costs. It is argued that differential-emphasis instructions should be modified in future research to find out whether children can sway more than under single-task conditions when instructed to do so.

The pattern of dual-task costs of the present study differed considerably from the pattern of the "Walking and Word Fluency" study (Krampe, Schäfer, & Baltes, in preparation), in which children and young adults were walking on a narrow track while concurrently performing a semantic word fluency task. In that study, 9-year olds showed dual-task costs for both tasks domains, while 11-year olds and young adults only showed dual-task costs in the walking domain. Therefore, the trade-off pattern of the "Walking and Word Fluency" study occurred only in the older age groups, and it was in favor of the cognitive instead of the sensorimotor domain. The discussion argues that the differences between the studies mainly lie in the use of different sensorimotor tasks, and in the fact that task difficulties have not been adjusted to individual performance levels in the "Walking and Word Fluency" study. Balance is probably a task that is not neglected if participants are already operating close to their stability limits, whereas walking slower is not threatening the body's equilibrium. In the "Walking and Word Fluency" study, both tasks might have been easier for the two older groups than for the 9-year olds, and the older groups were therefore able to keep up their cognitive performance in the dual-task situation.

Future research should take the characteristics of different sensorimotor tasks into account and explicitly investigate the influence of task difficulty on dual-task performance patterns. The following section presents some additional ideas for future studies.

6.6 Outlook

The present study showed that children allocate their resources differently than young adults when a sensorimotor and a cognitive task have to be performed concurrently. In the present study, children prioritized the sensorimotor domain over the cognitive domain, possibly to avoid loosing the body’s equilibrium.

Sensorimotor tasks. One interesting question for future research is whether this pattern is specific to balance as a sensorimotor task, or whether it generalizes to other sensorimotor tasks. There are indications from the “Walking and Word Fluency” study that walking on a narrow track might not be a task that children prioritize in a dual-task situation. However, the study by K.Z.H. Li et al. (2001) showed that older adults did prioritize the walking performance when concurrently performing an episodic memory task, but this pattern was more pronounced when the task difficulty of the walking task had been increased by placing wooden obstacles on the track. An interesting question is whether young adults would also start prioritizing the sensorimotor domain when the sensorimotor task becomes very difficult, for example when balancing on one foot with eyes closed. Another possible influence on prioritization behavior might be temporary decreases in young adults’ sensorimotor functioning, for example when they have to walk on a narrow track after having run a marathon the day before.

An alternative for balance tasks using the “quiet stance” paradigm, in which participants are instructed to sway as little as possible, would be to explicitly instruct people to move in a certain direction as far as they can, as in the “Functional Stability Boundary” tasks. Successful performance is then represented by *large* COP areas. The prediction would be that all age groups show dual-task costs for the balance task, by not leaning as far in specific directions under dual- as opposed to single-task conditions, but the performance decrement is expected to be more pronounced in children than adults. Therefore, although the resulting dual-task pattern would be the opposite to the present study (in which children actually improved their balance performance under dual-task conditions), the underlying reasons for the behavior would be the same, namely preservation of a safety region in balance tasks.

Practice versus maturation. Concerning changes in sensorimotor functioning during childhood, it would be interesting to disentangle the influence of maturation versus experience and practice. The underlying question is whether children mainly improve their sensorimotor skills over time because they accumulate hours and hours of practice in specific sensorimotor tasks, or whether maturational influences also play an important role, especially in younger children. It is therefore desirable to contrast groups of children who have received massive amounts of single-task practice for a specific task with those who have not, to see how these groups differ in a dual-task situation. Testing-the-limits methodologies (Kliegl, Smith, & Baltes, 1989, 1990) might be appropriate for these purposes.

Age groups. Another possibility is to test additional age groups with the current tasks, to see whether the trade-off pattern is even more pronounced than in the children of the present study. In older adults, balancing on the ankle-disc board might be more demanding than for children, due to changes in sensory systems with age (Kenshalo, 1977; Simoneau & Leibowitz, 1996; Sloane, Baloh, & Honrubia, 1989). The trade-off pattern might also be more pronounced in younger children.

Reinforcement. Since the reinforcement scheme in the differential-emphasis phase of the present study led to considerable performance improvements in all age groups, future studies should also investigate how performance can be influenced by systematically rewarding participants for certain performance patterns in a dual-task situation. It might not be motivating enough to simply instruct people to perform as well as possible, especially when younger children are tested.

Dual-Task Interference and Brain Imaging. Another interesting possibility to approach dual-task research is to also incorporate neuronal data. Methods like functional Magnetic Resonance Imaging (fMRI) and Positron Emission Topography (PET) are able to detect the areas of the brain which are active at a specific point in time during task performance, by measuring the cerebral blood flow or oxygen consumption. The amount of dual-task interference between two specific tasks might be predictable from the brain activation patterns they produce under single-task conditions. If many of the areas used for one task are also activated by the other task, interference is more likely to occur than when the tasks use distinguishable brain regions under single-task conditions. If these predictions can then be supported by behavioral data, interesting and potentially far-reaching implications for "classical" dual-task theories like the resource framework might result. For example, specific brain regions can be considered “resources”, and the fact that there are limits to the concurrent activation of brain regions can be interpreted as a limitation in available resources at any given point in time. The idea to refer to brain processes for the explanation of dual-task interference patterns is rather old (see Friedman, Polson, Dafoe, & Gaskill, 1982, or Hiscock & Kinsbourne, 1978, for similar approaches concerning the use of the left and right hemispheres), but the development of new methodologies in the brain sciences offers new and exciting opportunities for future scientific investigations. However, it might still be a challenge to measure brain activity during ecologically relevant sensorimotor tasks like walking or postural stability. Appendix N presents an overview of some neuroimaging studies that have incorporated dual-task situations.

Dynamic interactions between sensorimotor and cognitive systems over the lifespan. The present study and previous research using the ecological approach to dual-task research have shown that there are dynamic interactions between basic sensorimotor processes and cognitive functioning, and that there are age-related changes in these interactions. Older adults and children seem to invest more of their resources into the sensorimotor domain than young adults when faced with a challenging dual-task situation. However, much remains to be learned about the exact conditions under which these dynamics come into play. Additionally, future research should address the time-course of dual-task behavior more closely to be able to capture the dynamics of resource investment in an online fashion. For example, it would be interesting to see whether the concurrent cognitive task is harmed most in a situation in which an individual is approaching his or her personal limits of stability in a balance task.