Choking under Pressure –

Attention and Motor Control in Performance Situations

Dissertation

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Acknowledgments

During a time when a German “summer fairy tale” almost came true because the German soccer team was close to winning another world cup and even (may be because…) a sportpsychologist was sitting on their bench – I had to write my dissertation! When watching a game, though, I was hoping to witness a moment of “choking”, someone missing a clear goal, something I could use as an anchor in my introduction. But unfortunately in the only moment of choking that I saw, someone lost his head but with it he didn’t miss his goal... So, instead of examining the topic of the dissertation life on TV, I had to analyze and interpret data from dubious laboratory experiments. Dubious, that’s probably what most of the participants in my experiments thought of the tasks they had to do. To them I have to express my deep gratitude – this dissertation would be purely theoretical if it hadn’t been for them! In this context, I’m indebted to David Conroy who offered his students credits for my experiments. The significant part of this dissertation ows to my two stays at Penn State – thanks to the people in the Action Lab, specifically Kunlin “Dr. K.” Wei, for their openness, critique, advice and help. The tracking task would not have been possible without the programming skills of Jonas Lorenzen – he produced a high-end product on a low-budget. Whereas the participants doubted the tasks, the student assistants in Potsdam must have doubted my mental health – still they spent endless hours in analyzing the tone-judgment tasks. I’m also grateful to the entire “teams” in Potsdam but also, since recently, in Munich – both provided the atmosphere that this dissertation could come to a (hopefully) successful end. But I do want to pick out Enrique Silva-Cousino and Christian Heiss, who have for long and for short helped me stay sane by giving plenty opportunities to re-focus.

The thoughts and ideas of many went into this work, although only the ones I read about I could cite. Beyond these papers, my discussions at the Action Lab, my presentations in Heidelberg, Giessen and our Winterakademie in the Kleinwalsertal proved seminal to this dissertation– my gratitude to all who contributed. Further this is a good opportunity to thank Prof. Ernst-Joachim Hossner for stimulating my work and for pushing me to the idea that was realized in Study 2. Always honestly critically following this dissertation was Dr. Daniel Erlacher, to whom I’m deeply in debt. His questions, ideas and corrections significantly contributed to what good there is in this work.

This dissertation had three advisors, my grateful thanks to Prof. Reinhold Kliegl who steered the dissertation to this end by intermittently giving me (and my work) his

full attention and asking the right questions, to Prof. Dagmar Sternad, for giving me the opportunity to stay at her lab, for all the feedback and the continuous support, and to Prof. Beckmann, who let me do "my thing" and never seemed to have any doubts that it would have a good ending – I'm looking forward to addressing some of the issues raised by this dissertation in Munich.

"Choking under Pressure" is only the topic of my dissertation, not the theme of my life – this is owing to my wife, Lena. With her help, I feel I can survive any pressure.

Introduction

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July 17th 1994, Rose Bowl, Pasadena, just after 3 pm. Carlos Dunga has just scored to give Brazil the lead in the decisive overtime penalty kicks in this soccer world cup final. And it is now up to Roberto Baggio to keep the Italians alive. But Baggio ends the game for good - his kick sails above the cross-bar. It is these infamous and memorable moments that make sports so fascinating - both for watching as well as performing. And it is these moments that make studying sports and sports performance so interesting: Why did Baggio miss the goal? This question has not only left all of Italy wondering but the same question has been asked by researchers in more general terms: why do athletes "choke under pressure"?

This question is at the heart of this dissertation. And it has already been addressed from different perspectives. For example it has been investigated whether certain types of personalities can be found that are "prone to choke", or whether it depends on the task performed that people choke – or not. But the question of "why" goes deeper than merely identifying antecedents or conditions of choking. It also asks for the processes or mechanisms involved. This is where this dissertation is aimed and therefore the original question may rather be phrased as "*how* do performers choke under pressure". This question has been addressed by research, as well. It has found the phenomenon of choking to be an attentional phenomenon, because it appears that under pressure the focus of attention is shifted from automatic to controlled processing of the task. Despite the identification of such a cognitive process it is not known how this affects the coordination or control of the movement itself. In fact, little research has been done to investigate movement execution under pressure. Thus, an understanding of the sensorimotor processes involved in choking is still missing. The cardinal question of this dissertation is thus the search for a sensorimotor mechanism behind choking under pressure.

The Problem – Choking under Pressure

Before analyzing the phenomenon of choking, the conditions under which it occurs and the potential processes that are involved, first the phenomenon has to be described in more detail. A first question that has to be addressed is what „pressure“ means or how it is understood, even if everyone can agree that Baggio must have felt „under pressure“. Baumeister and Showers (1986) defined "pressure" as the presence of situational incentives for optimal, maximal, or superior performance“ (p. 362). These incentives are given in varying situations and thus there are different forms of pressure situations. According to Baumeister and Showers (1986) pressure arises when a reward or a punishment is contingent upon the performance in the situation. The presence of an audience increases incentives to do well and thus leads to pressure. Furthermore, singular situations or performances also add to pressure, when there is no second chance to alter the outcome of a performance. Usually, this performance also needs to be „important“, either to others or to oneself. Especially if the performance has some ego-relevance, i.e. performance is indicative of important aspects of the "self" the pressure is increased. Finally and most importantly, competitions in which performance is compared between (co-)actors are pressure situations.

Although (or maybe even: because) this is the only concise definition of pressure, it is certainly disputable. The mentioned forms of pressure vary with respect to their inherent subjective nature: for example, an audience, contingent effects or a coactor/competitor are objective features of a situation but the significance of a situation is clearly subjectively attributed to that situation. Furthermore, situations fraught with objective characteristics of pressure may not be *perceived* subjectively as pressure situations – penalty kicks may be fun to Carlos Dunga but (apparently) not to Roberto Baggio. To disentangle the objective and subjective components a reference needs to be made to cognitive theories of stress and emotion. Within cognitive-transactional models of stress and emotion (e.g. Lazarus & Folkman, 1984) psychological stress is seen to develop from the subjective appraisal of objective stressors. Only if these stressors are evaluated as threatening or harmful to the current person-environment relation, stress is experienced. The first evaluation (or primary appraisal) is mainly concerned with determining "whether anything is at stake" (Lazarus, 2000, p. 54). Only if something is "at stake" stress may be perceived, but whether a stressor is perceived as stressful further depends on a number of moderators (such as personality e.g.) and mediating processes (or secondary appraisals such as the evaluation of resources). In the context of performance under pressure this means that clearly objective features have to be separated from the subjective experience of pressure which depends on moderating and mediating variables. For example, an audience may be subjectively perceived as pressure only if a performer attributes importance to the positive evaluation of that audience – which is at stake if he performs poorly. In the cognitive-transactional frame of reference pressure can than be defined as follows: *A situation in which a person perceives something being at stake* *depending on the outcome of one's performance.* "At stake" could be objective (like a financial reward) as well as more subjective features of the situation (like social status or even personal standards), but relevant is the perception that it *is* at stake. In the case of Baggio's dismal kick we can assume that not only Italy but Baggio himself perceived a number of things being at stake, among them of course the world cup.

"Choking", as defined by Baumeister and Showers (1986), is the "occurrence of suboptimal performance under pressure conditions" (p. 362). Some further criteria are, however, attached to that definition: Most importantly it must be certain, that the performer wants to perform well in that situation. One can also only speak of choking, if the performer has already established a certain standard of performance. Baumeister and Showers (1986) use a broad definition of performance: any situation in which the goal is immediate, maximal achievement. This can be distinguished from practice situations, in which long-term improvement is the goal. Thus performance is possible on all levels of skill, and therefore choking (in pressure situations) maybe observed at any level of expertise. Finally, choking refers to a single poor performance. If poor performance occurs over a longer stretch of time, the term slump is used (Taylor, 1988). However, the problem with single events is that they may not be objectively or reliably defined, because they could be expressions of chance effects – which would restore Baggio's reputation.

Obviously, performers do not always (and not all performers) choke in pressure situations. Otherwise Carlos Dunga would have missed his penalty kick, as well, or we would never see world-records at Olympic Games, for example. A major line of research into the phenomenon of choking under pressure is therefore concerned with the conditions under which choking occurs. Interestingly, some of that research has been done under the topic of „social facilitation", expecting quite contrasting effects of pressure situations (cf. Strauss, 2002) and using quite strange subjects (e.g. Zajonc, Heingartner & Herman, 1969). This research has discovered a number of moderators in the pressure – performance relation and they will be presented below. But even if one knows the antecedents or conditions of choking, the question remains why or how these conditions lead to choking. This question refers to the processes that are going on in the pressure situation that lead to poor performance. The search for such mediators in the pressure – performance relation is thus presented as the second line of research.

Because this dissertation aims at revealing the processes occurring under pressure, this research will be presented in more detail.

Search for moderators: conditions

As mentioned above, pressure does not always lead to performance decrement. Psychological research has identified a number of factors that moderate that relation. These moderators may be categorized from an action-theory viewpoint into aspects of the situation and environment, of the person and of the task (Nitsch, 2004). They do, however, also interact.

Regarding the situation, the presence of an audience is first and foremost a form of pressure and thus cannot simultaneously be a moderator. But research has found that certain aspects of the audience do play a moderating role (Baumeister & Showers, 1986). For example the size of the audience, its (perceived) status and its salience appears to influence the importance of the situation and consequently performance. But more importantly the expectancy of the audience seems to be crucial: if performers feel they have to perform up to spectators' expectations, they appear more likely to choke (e.g. Baumeister, Hamilton & Tice, 1985).

The main focus of identifying moderators has been on the person, i.e. on individual differences. It is based on the belief that some people are more vulnerable to pressure and are thus prone to choke, whereas others just strive under pressure. Trait anxiety has been one of the main personality characteristics investigated but most experiments have been conducted using cognitive rather than motor or athletic tasks. In these tasks anxiety is generally positively related to performance decrements. A study by Wang, Marchant, Morris and Gibbs (2005) also found that athletes high in somatic anxiety were more likely to choke under pressure in an athletic setting. Furthermore, they found a positive relation between self-consciousness and choking, with athletes high in private self-consciousness showing poor performance. This is contrary to many other findings that show that persons low in dispositional self-consciousness are susceptible to choking (cf. Baumeister, 1984). It has been hypothesized that pressure leads to self-awareness (see below), which interferes with performance. People with high dispositional self-consciousness are, however, accustomed to this self-awareness and their performance is thus not disrupted (Baumeister & Showers, 1986). In action-control theory (Beckmann, 1992) these disruptions are conceived of as "obstacles" on the way to excellent performance, and action-control processes are necessary to overcome the obstacle. In a study by Beckmann and Strang (1992) persons with deficits in action- control (in this case with a dispositional "state-orientation") initially had difficulties to overcome these obstacles in a complex (cognitive) task and thus showed reduced performance compared to persons without such action- control deficits. Hence action-/state-orientation appears as another moderator. Some researchers have also argued for skill-level as another moderator. Even Baumeister and Showers (1986), who explicitly included novice performance in their definition of performance (see above), admit that pressure may have a stronger influence on performance, as skill level increases. Within the explicit-monitoring models it is also crucial to choking that an expert level has been achieved where skills are executed "automatically" (Beilock & Carr, 2001). Furthermore it may be speculated that the skill-level has effects on the perceived self-efficacy and self-confidence. The expectancies of failure or success have been repeatedly shown to moderate the response to pressure. In an experiment by Bond (1982) subjects showed increased performance when they had previously experienced success but performed poorly after previous failure. Woodman and Hardy (2003) conducted a meta-analysis on the relation between scores on the competitive state anxiety inventory (CSAI-2, Martens, Burton, Vealey, Bump & Smith, 1990) and competitive sport performance. They found a significant correlation only for the subscale measuring self-confidence.

The third category of moderators is the type of task. Most of the research, especially within the "social facilitation" approach (e.g. Zajonc, 1965), has been concerned with a simple vs. complex distinction. In the original Zajonc-model it is proposed that pressure (through the presence of others) facilitates simple tasks and inhibits complex tasks. Empirically this assumption is hard to hold, as the meta-analysis by Bond and Titus (1983) shows. The lack of sound empirical evidence is due partly to the operationalization and definition of "simple" and "complex", especially in the domain of motor tasks (Strauss, 2002). There are no clear cut criteria for the dichotomization, and often properties are assigned based on the amount of experience with a task (a novel task being complex vs. a well-practiced task being simple), based on the person (poor performance is indicative of a complex task), or based on the task domain (cognitive equates to complex, motor to simple). Other distinctions refer to the type of performance and have found more consistent support. In the Bond and Titus (1983) meta-analyis it was revealed that performance in tasks requiring a quantitative performance (measured in terms of time or weight) benefited from pressure, whereas tasks requiring qualitative performance (measured in terms of accuracy, consistency or number of errors) were performed worse under pressure. Motor tasks can be very closely matched to this quantitative/qualitative distinction when conditioning tasks are discerned from coordination tasks (Strauss, 2002). Performance in conditioning tasks is evaluated quantitatively whereas performance in coordination task is mostly evaluated qualitatively. While results are somewhat inconclusive for tasks with high coordination demands, performance in conditioning tasks usually benefits from a pressure situation (e.g. Beckmann & Strang, 1992).

Moderators influence a direct relationship and in the context of performance under pressure features of the situation, the person and the task have been identified as such moderators. They influence whether pressure in a situation leads to facilitation or inhibition of performance. The next question to ask is how pressure leads to changes in performance and also how the moderators work on the direct relation. In fact, much of the research on moderators was stimulated by the proposed processes behind the relation.

Search for mediators: processes

Two general approaches may be distinguished in the search for mediating processes, a drive-theory and an attentional-theory approach. The former originated in social psychology and the work on social facilitation (e.g. Zajonc, 1965), the latter has developed in part from criticism of the drive-approach and has gathered more evidence over the years.

Drive-theories

Drive-theories hold the assumption that task performance depends on the level of "arousal" of a person. One version of the drive-theories postulates an inverted-U relation between performance and arousal or "drive" and primarily refers to the seminal work by Yerkes and Dodson (1908/2006). They found that rats were able to learn more quickly to discern "safe" from "unsafe" areas, when they were electrocuted with medium level shocks. Methodologically it can be criticized that it is not possible to measure "drive" directly and in absolute terms. Although this criticism has been attempted to meet by defining drive as "physiological arousal" the problem remains that no single physiological measure may be identified as a general measure of arousal (Beckmann &

Strang, 1992). Besides the problem of choosing the right measure (cardio-vascular variables, central or peripheral variables) Carver and Scheier (1981) pointed out that choosing the right time to measure is of relevance: they found increased activation not during task execution but only during breaks. Bandura (1977) also argues that activation or arousal and performance appear to be related, but that a direction of causal effects is hard to detect, therefore they should be considered as co-effects.

From a theoretical perspective it needs to be criticized that potential processes that underlie the changes in performance are mostly neglected (*why* does arousal lead to performance decrement?). Only some studies have addressed this issue. For example Easterbrook (1959) postulated that arousal changes the range of the focus of attention: High arousal should lead to a narrow focus of attention, whereas low arousal leads to a broad focus of attention and the processing of task irrelevant stimuli. A second version of the drive theories are the so-called "dominant-response-theories", that state that increased drive increases the likelihood of dominant responses. Simple tasks and well-learned skills should therefore not be impaired by pressure situations because successful execution is the dominant response in these tasks. In complex or novel tasks, however, the dominant response is failure – thus pressure should lead to poor performance. As the reported Bond and Titus (1983) meta-analysis has shown, this assumption stands on weak empirical grounds. And for sport performance, where the dominant response is certainly undisturbed performance, the assumptions contradict obvious experience. Roberto Baggio probably didn't miss the goal in practice and in most games (i.e. scoring or at least getting the ball to the goal is the dominant response) but he missed it in the world cup final!

Attentional theories

Attentional theories assume that performance changes under pressure are due to altered cognitive processes. Two main views exist, that may not be mutually exclusive (Lewis & Linder, 1997) and that link performance decrement to distracted attention on the one side and to self-focused attention on the other.

The distraction-theories assume that under pressure actors do not focus their attention on task-relevant stimuli. Two mechanisms are in debate within that approach: either the selective function of attention is impaired (potentially due to capacity limitations) and an increased amount of information is processed which leads to the neglect of relevant information, or the focus of attention is shifted to task-irrelevant stimuli and critical features are thus missed (cf. Baumeister & Showers, 1986). An important type of such irrelevant stimuli are the so-called „worry“-cognitions. Their negative effect on performance in pressure situations have been shown in a number of studies (cf. Schlicht & Wilhelm, 1987; Späte & Schwenkmezger, 1983).

The self-focused attention-theories assume that under pressure actors turn their focus of attention inward. Again two somewhat alternative approaches exist. Self-awareness theories propose that increased pressure induces heightened self-awareness (e.g. Carver & Scheier, 1981). Increased self-awareness leads to becoming aware of discrepancies between a personal standard (the ideal behavior or state) and the actual current behavior or state. The perception of a discrepancy leads to increased effort but also to repeated comparison between the standard and possible courses of action. This comparison needs time and therefore leads to poor performance, either because speed of action is reduced or because a poor option is chosen. The Bond and Titus (1983) meta-analysis lends some support for that notion, because they found reliable performance decrements in qualitative performance in complex tasks and reliable performance increments in quantitative performance in simple tasks. Explicit monitoring theories have a slightly different approach. Here, it is assumed that under pressure actors have the desire to do well, which leads to focusing on the process of performing (Baumeister, 1984). Focusing on or controlling the execution of the processes (i.e. “explicitly monitoring” the process) then leads to the disruption of these processes. Behind this approach is a certain concept of (motor) skill acquisition. In this concept it is believed that during learning a skill, learners pass from a cognitive to an autonomous (Fitts & Posner, 1967), from a declarative to a procedural (Anderson, 1982), or controlled to an automatic processing stage (Schneider & Fisk, 1983). Thus motor skills are generally thought to be executed “automatically” at an expert stage and they do not need conscious control to be executed correctly. Under pressure, due to explicit monitoring, a “reversal” takes place and the usually automatic processes are consciously controlled. This then leads to a step-by-step control and execution of the task (e.g. Beilock & Carr, 2001).

In a study by Lewis and Linder (1997) participants learned to putt a golf ball. Performance during learning of half of the participants was recorded with a video camera to raise self-focus. In a pressure situation (manipulated through financial incentives) following the learning phase, half of the participants had to also solve a cognitive secondary task (to induce distraction). Results indicate that pressure only lead to poor performance either if participants were *not* distracted or if they were not adapted to self-focus (through prior video-recording). Similar results were found by Beilock and Carr (2001), who transferred the additional cognitive load through a dual task into the practice phase. In a first experiment participants learned the golf-putt either as a single task, in a dual task with an additional word-counting task, or with their performance being recorded with a video camera. In the final pressure situation (fake competition with financial incentives) consisted of only the single task of putting. Again, best results were seen in the self-awareness group (learning with video-recording) but there was no difference between the two other groups. In a second experiment, participants again learned the golf-putt in either the self-focus (video recording) or dual-task condition (word counting). In a (single-task) pressure test early in the practice phase, no differences were found between groups. But in the final pressure test (after 300 putts) the self-focus group made significantly fewer errors than the dual-task group. Beilock and Carr (2001) interpret this finding as providing evidence fort the hypothesis that in the beginning, when the skill is not yet "proceduralized" the explicit monitoring of the task, induced through the pressure situation, enhances learning. However, at the end, when the skill may be executed automatically, explicit monitoring leads to performance breakdown. Practicing under conditions of heightened self-focus inoculates against these detrimental effects via two routes: adaptation to an increased performance pressure and habituation to performing under heightened self-focus. Further evidence for explicit monitoring theories comes from a line of research originated by a study by Masters in 1992.

He started with the observation that the acquisition of motor skills does not necessarily follow the succession of declarative to procedural knowledge stages. In fact, many everyday motor skills are acquired implicitly, that is without being given or acquiring explicit knowledge about the task. We learn to use the grammatical structure of language long before we are taught it in school, we learn to crawl, walk or run without being able to tell, how we are doing it. This absence of the facility to verbalize the knowledge that has been acquired is one criterion of implicit knowledge (Frensch, 1998). Masters now assumed that if during learning no declarative knowledge about a task is acquired, then under pressure there should be no explicit knowledge availabe to control the skill. Thus, implicit learning should inoculate against choking under pressure. Participants learned to putt a golf ball and were assigned to five experimental groups, an "implicit group" (learning under dual-task conditions), an "explicit group" (receiving a set of rules), and a control group. After the learning phase (400 putts) a retention test followed in which half the participants in the implicit and control groups ("stressed-implicit" and "stressed-control" groups) entered a pressure situation. Similar performance increments were found between groups across the learning phase. In the retention test, however, performance decrements were only found in the (non-stressed!) explicit group and the stressed-control group. Hence, implicit learning appeared to prevent choking. Hardy, Mullen and Jones replicated this experiment in 1996 and also added a group that continued to carry out the dual-task in the pressure test. Again, implicit and non-stressed control groups increased performance, in contrast to the explicit group that "choked" under pressure. Thus, the performance enhancement of the implicit groups in the original Masters (1992) study can not be attributed to discontinuation of the secondary task. In a more applied setting Liao and Masters (2002) showed that giving explicit instructions during learning compared to a "do-your-best" condition impaired performance in a subsequent pressure test, lending further support for Masters' (1992, 2000) "reinvestment-hypothesis".

To summarize, although the effect of distracted attention under pressure may not be ruled out there exists ample experimental evidence that performance decrement in pressure situations is linked to self-focused attention. It appears that this self-focus leads to an "explicit monitoring" of the task and its execution, consequently impairing performance.

Inconsistencies, problems, and open questions

As mentioned above, Masters (2000) and Beilock and Carr (2001) interpret their results very similarly as indicating that pressure leads to explicit monitoring of a task and to subsequent performance decrement. A closer inspection of the studies raises concerns whether they warrant such a mutual interpretation. Again, Beilock and Carr (2001) or Lewis and Linder (1997) found that training under conditions of increased self-focus inoculates against choking under pressure, whereas Masters (1992) and Hardy, Mullen and Jones (1996) found that directing the focus of attention towards skill execution during learning impaired subsequent performance under pressure. Beilock and Carr hypothesize that their participants grew accustomed to the self-focus induced explicit monitoring, which prevented choking. The same should have happened to the participants learning under skill-focus conditions in the studies by Masters (1992, Liao & Masters, 2002), however, here skill-focused learning lead to choking. These different effects of a (more general) self-focus through video recording versus a (more specific) movement- or internal focus of attention through instructions may point to different processes involved. In the self-focus condition participants might have developed action-control strategies to overcome the "obstacle" of the self-focus (cf. Beckmann & Strang, 1992). They were able to employ these strategies in the following pressure situation, so that explicit monitoring might not even have occurred with these participants. Furthermore, they might not have experienced as much pressure as participants without the prior self-focus training. Unfortunately anxiety was not measured in either the Lewis and Linder (1997) or the Beilock and Carr (2001) study. Learning with explicit instructions that induced an internal- movement directed focus of attention in the Masters studies did not provide an opportunity to learn action- control strategies, hence explicit monitoring of the task could not be prevented under pressure. Still, all of these reported studies indicate that explicit monitoring of a task is behind the phenomenon of choking under pressure.

But more critically, all the reported studies have left it rather vague, how "explicit monitoring" leads to the performance breakdown. Two important problems are connected to that observation: first of all, there are no clear proposals for a mechanism on a level of motor control Masters (1992, 2000) assumes on a merely cognitive level that "the recruitment of working memory resources in explicitly learned skills can interfere with the efficient control of movement"(Masters & Maxwell, 2004, p. 210) but makes no explanation as to *how* working memory interferes with movement execution other than saying that the skill is "deautomatized". Only Beilock, Carr, MacMahon, and Starkes (2002, p. 8) have undertaken an attempt to formulate a potential mechanism on a more sensorimotor level. They assume that the entire movement structure or "chunk" is broken down into smaller units. The sequence of smaller units resembles movement organization during learning of the movement. Explicit monitoring leads to the individual activation and production of the smaller units, which should take more time and leave more opportunities for errors. The second problem is that both, the more cognitive as well as the more sensorimotor mechanism have not been tested so far but have only been inferred by testing the direct relation between pressure and performance! In all of the studies reported so far, the performance situation is manipulated to induce pressure and then the performance *result* is measured. The performance itself is not analyzed, although it is believed that it is altered. This „black-box"- approach is not sufficient, if one really wants to understand the processes involved in the phenomenon. Neumann (1992) for example has demanded that for the understanding of mechanisms the integration of several levels of analysis is mandatory, and this certainly includes the analysis of processes occurring on a movement or sensorimotor level.

Very few studies have looked at how movements are executed and what changes occur under pressure, thus looking at the processes involved. Gray (2004) has been the first to test whether performers under pressure do focus their attention on the movement. He had participants perform a baseball batting task and either a movement related or an extraneous secondary task (judging the occurrence vs. the pitch of a tone). Participants performed better in the movement related task when in the primary baseball task they were under pressure experiencing a "slump". This was interpreted as giving evidence for an internal-movement directed focus of attention under pressure. Also some studies have looked at kinematic changes under pressure. Mullen and Hardy (2000) found no clear evidence for systematic kinematic changes in a golf putting task. Higuchi (2000), using a ball throwing task, found increased variability of joint coordination but reduced variability of the release point under stress, which was accompanied by impaired performance. Higuchi, Imanaka, and Hatayama (2002) used an artificial interceptive task and found delayed movement initiation and reduced variability of spatial kinematics under stress. This was interpreted as a shift towards constrained execution under pressure. Finally two studies are more closely related to the assumed explicit monitoring under pressure. Both studies tested whether there was evidence for a regression in movement execution to early stages of learning the skill. The studies are based on the original ideas by Bernstein (1967) that learning a motor skill is accompanied by a gradual release of degrees of freedom. It was consequently hypothesized that under pressure, a "re-freezing" of degrees of freedom should occur (Vereijken, van Emmerik, Whiting & Newell, 1992). Pijpers, Oudejans and Bakker (2005) examined the performance of rock-climbers in two different heights, assuming that a higher climb would induce anxiety and "pressure". Using an index of the smoothness of a climber's trajectory they were able to show that performance in the high-condition resembles climbing behavior of less experienced climbers, thus indicating a regress to an early stage of motor learning. Collins, Jones, Fairweather, Doolan and Priestley (2001) were also able to detect functional changes on a process-level under pressure. In their first study they also used "height" to induce anxiety. Trained soldiers were asked to perform a complex stepping task either at ground level or on a platform at 20m height. Similar to the findings by Higuchi, Imanaka, and Hatayama (2002) they found less variable movement patterns at height. In a second study they examined weight-lifting performance in lifters at a championship competition and at practice. They interpreted the rather qualitative analysis of kinematic data and of the post-performance interviews as indicating consciously mediated performance under pressure.

The latter studies altogether pose a major step towards investigating and understanding the processes involved in the phenomenon of choking under pressure. Not only are they looking at performance itself and how it changes, but they are also making assumptions about what type of changes should be expected, if a movement is under "conscious control" or "explicitly monitored". However, there are still no clear ideas of how the skill-focused attention or explicit monitoring leads to the constrained execution found in these studies. The proposal by Beilock, Carr, MacMahon, and Starkes (2002) is certainly a first step towards theoretical underpinning, but it leaves open, how and why "chunks" develop, at what points they should "break up" under pressure and how this leads to constraint and faulty execution. What is needed is a theory that proposes in detail a sensorimotor mechanism behind the phenomenon of choking under pressure. This proposal needs to make clear predictions (1) as to what changes on a kinematic level should occur as a consequence of a movement directed focus of attention under pressure and (2) how and why they occur. In the following, a hypothesis is presented that is assumed to provide for such a mechanism.

A Solution? – The Nodalpoint Hypothesis of Motor Control

The last years have seen a mounting of empirical evidence that focusing one's attention on the effect of a movement enhances learning of that movement or motor skill (cf. Wulf & Prinz, 2001). This has been shown in laboratory tasks as well as in applied settings (Wulf, Höß & Prinz, 1998; Wulf, Lauterbach & Toole, 1999), and also some generalizations (feedback: Shea & Wulf, 1999) as well as constraints have been found (Wulf, McNevin, Fuchs, Ritter & Toole, 2000). Although other investigators have questioned the generalizability of the results (Ehrlenspiel, Lieske & Rübner, 2004; Perkins-Cecatto, Passmore & Lee, 2001) the overall impressive empirical findings show that an external focus of attention enhances learning. But similar to the phenomenon of choking under pressure, formulations of possible mechanisms behind the advantage of an external-effect oriented focus of attention have been rather vague. McNevin, Shea, and Wulf (2003) formulated a "constrained action hypothesis" which assumes that two processes underlie motor control and learning, a conscious and an automatic process. If performers direct their attention to their body movements this conscious intervention "constrains" the motor system and leads to the disruption of automatic processing. Directing attention to the effects the movement has in the environment, however, allows the more automatic and unconscious processes to take over movement control. As Hossner (2004) and Ehrlenspiel (2001) analyze, a suggestion for the detailed sensorimotor mechanisms underlying the resulting breakdown is still missing. Therefore they propose a nodalpoint hypothesis of motor control (Hossner & Ehrlenspiel, 2006).

The nodalpoint hypothesis and its four threads

The nodalpoint hypothesis of motor control is developed from four threads which may be labeled as (1) the ideo-motor principle and SRE-units, (2) serial chaining and end-point control, (3) de-freezing and muscular activity and (4) exploitation and compensatory variability.

Ideo-motor principle

Based on the thoughts by William James that "our idea of raising our arm ... or crooking our finger, is a sense ... of how the raised arm or the crooked finger feels" (1891/2001, p. 499) the ideo-motor principle assumes that movements are coded in terms of the effects they evoke. This idea originated from introspection but– after some decades of rejection – has both found expression in a number of theoretical works (most notably the concept of anticipatory behavioral control by Hoffmann, 1993) as well as empirical support. Evidence comes mainly from testing the key prediction that motor actions should be activated by presenting the effects they elicit. A typical experiment in this context of "response-effect-compatibility" was conducted by Kunde (2003) where participants had to react to two color stimuli with a key-press. Each stimulus (color bar on a monitor) required either a short or a long key press. Key-presses (i.e. the "responses") were followed by a tone (i.e. an "effect"), either of compatible (short-short, long-long) or incompatible (short-long, long-short) duration. Participants' responses were faster to compatible than to incompatible responses. This effect remained even if the reaction was primed and was executed after a neutral go-signal (Experiment 2), indicating that response-effect compatibility effects extend from movement selection to movement initiation stages of movement control (see also Elsner & Hommel, 2001; Kunde, 2004; Kunde, Koch & Hoffmann, 2004). The important contribution of the concept of ideomotor action to the nodalpoint hypothesis is that behavioral units consist of the initial conditions given by the situation S, of a response R, and its sensory effects E (Hoffmann, 1993) and, that in those SRE-triplets responses are governed by their anticipated effects (i.e. the intended goal). Furthermore, as formally expressed in the common coding approach by Prinz (1997), perceived stimuli and perceived effects basically fall into the same category of perceived "events", and for this reason every perception may be considered as the perceived effect of the previous elementary act – whether this act was actively produced or passively witnessed. Putting it together, there is nothing else to perceive from the movement than those effects and therefore focusing attention necessarily refers to effects of elementary behavioral acts.

serial chaining and endpoint control

Hoffmann, Stöcker and Kunde (2004) were able to show that irrelevant tone effects also facilitated movement *chunking*. Participants learned 3- and 6-element sequences of key-presses under conditions where key-presses had either contingent distinct tone effects or no tone effects, respectively. In a test phase, participants in the contingent-tone-effects condition initiated sequences faster and had shorter inter-response times compared to participants in the no-tones condition. In addition, only in the no-tone group differences between the two sequences were found. Obviously, the additional external effects of the key-presses, although completely irrelevant for the task, helped in the formation of movement chunks. Greenwald (1970) and Hoffmann (1993) speculated that if in the process of learning effects are accurately and reliably attained they can be serially chained to form a "chunk": The experience of contingent SRE-triplets first leads to a shift in execution control from stimuli to anticipated effects. When these effects then follow each other reliably, they become associated and form a sequence. Eventually, the final effect takes over the control of the entire sequence. Empirically, in a very similar vein but for a complex motor skill, Bootsma and van Wieringen (1990) found a "homing in" of movement parameters, as e. g. the variance in the direction of the bat's travel declines until the moment of ball-bat-contact. Apparently the movement was controlled from the final effect backwards rather than from the point of movement initiation or by continuous guidance, as might be expected from other theories of motor control. (e.g. Adams, 1972; Schmidt, 1975)

Important for the formulation of the nodalpoint hypothesis of motor control is that during motor learning, chunks of SRE-triplets evolve, and with the formation of such chunks, the control is shifted from single units to the end-effects of the entire chain of effects.

de-freezing and muscular activity

Bernstein (1967) originally formulated as the central problem of motor control how the body's multiple degrees of freedom can be controlled. During motor learning this problem is met by initially constraining the degrees of freedom to ensure control. But eventually across different stages of learning these degrees of freedom are freed in order to allow for more efficient movements. Some empirical evidence for this "(de-)freezing of degrees of freedom" exists: Vereijken, van Emmerik, Whiting and Newell (1992) have shown that in a novel motor task (moving on a ski-simulator) beginners indeed tried to constrain the system by reducing degrees of freedom. Changes in task performance (greater amplitudes of the platform) across learning were accompanied by an increase in variability of body angles and a decrease of cross-correlations between joint angles. This "de-freezing" in terms of de-coupling of adjacent joints was taken to support Bernstein's idea of a gradual release of degrees of freedom as learning progresses. Further support comes from a study by Cordier, Mendès France, Pailhous, and Bolon (1994), who found smoother trajectories in novice free-climbers as learning progressed, indicated by a smaller "geometric index of entropy". One feasible way to reduce the degrees of freedom of a motor skill and to "freeze" the system is to increase joint stiffness and rigidity through antagonistic muscular co-contraction. Accordingly, in a pointing task, Newell, Challis and Morrison (2000) found that although increased limb stiffness through increased muscular co-contraction constrained the segments of the upper limb successfully, the stiffness additionally led to an increase in the tremor of the pointing index finger, i.e. to noisier endpoint variance.

Again, taken together, it appears that to overcome the vast degrees of freedoms in controlling a motor skill, the body and body segments are rigidly fixed through antagonistic muscular co-contraction. This constraining of the motor system leads to increased movement variance. Over the course of learning this fixing of the skill is gradually released.

exploitation of task properties and compensatory variability

Beyond freeing of the degrees of freedom of a motor skill, Bernstein suggested that the highest stage of learning allows the utilization or exploitation of "reactive phenomena in a system" (1967, p. 109). Beyond such phenomena as gravity and other forces, it may be speculated that given properties of the motor system may be exploited. The stable performance at the expert level of motor learning would then be a product of a *functional* coupling of movement parameters, rather than the rigid coupling found in the initial stage. This functional coupling can be evidenced in a covariation or compensatory variability of movement components, in which deviations in one component are compensated for by the fluctuations in other components (see e. g. Loosch, 1997). Not surprisingly, numerous studies have found evidence for the use of covariation or compensatory variability in expert performance. A famous study was conducted by Arutyunyan, Gurfinkel and Mirskii (1968) who found that the aiming in pistol shooters was very stable despite continuous fluctuations in the joints of the arm holding the pistol. Other properties of the task may be exploited as well. For example, in a study by Sternad, Katsumata, and Schaal (2000) participants learned to (implicitly) exploit dynamical stability in a ball bouncing task.

Thus, expert performance not only sees the release of degrees of freedom (thread 3) but seen together, it can be speculated that these degrees of freedom are used or "exploited" for compensatory variability in order to produce stable behavior.

The nodalpoint hypothesis of motor control

Based on these four threads the nodalpoint hypothesis of motor control (Hossner & Ehrlenspiel, 2006) now assumes that (1) in the process of motor learning chains of SRE-units are formed and that initially there is a need to attend to the effects of each single triplet (see Figure 1 A). For example a young child will have to focus his hands grasping a cup in order not to spill its contents but the reader of this dissertation does not and may therefore grasp the cup and read at the same time. This is possible because (2) chunks of SRE-units developed, and there is less need to attend to effects of intermediate responses that only serve as sub-goals en route to a final action goal - the endpoint's final effect that also takes over control of the entire sequence. The attainment of those sub-goals then does not need to be attended to anymore as the associated effects appear to happen increasingly reliably (see Figure 1 B). In addition to this change in control structure the system is "freed". Optimization processes concerning exploitation of the system's properties are no longer restricted to processes within a basic unit, but may be extended to chunks of units. Thus an inaccurate attainment of a certain sub-goal may be compensated for by a functional adaptation of the subsequent unit. Still, (3) the previous effects within the sensorimotor chain may still serve as anchors – as *nodalpoints* of action sequences –, i.e. they still *may* be attended to. While the reader does not need to attend to grasping the coffee cup while reading this dissertation, he or she can certainly do so and will, as soon as the handle is missed or the handle slips (see figure 1 C).

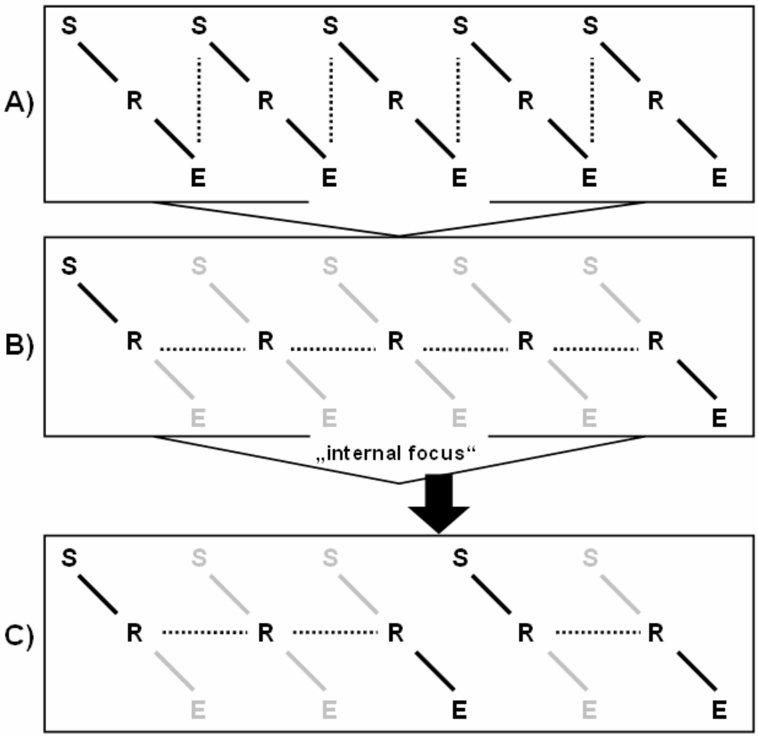

Figure 1. The nodalpoint hypothesis: Movements are seen as constituting a sequence of stimulus, response and effect triplets. While initially during learning the attainment of each effect needs to be controlled (A), eventually the final effect takes over control (B). Nodalpoints, the intermediate effects in the chain of SRE-triplets, serve as anchors for focus of attention. Focusing, however, leads to a breaking up of the chain (C).

Nodalpoints are therefore clearly distinguishable effects and essentially goals of elementary behavioral acts. Elementary acts may not be divided into further parts without changing the purpose of the action. More importantly, "prominent" nodalpoints exist at boundaries of "chunks" of sub-goals or effects, when there is a relative uncertainty of attainment. This uncertainty develops when at least initially sub-goals are not consistently attained. This is the case in open or interactive tasks where effects depend on the (re-)actions of the environment. But it is also notable for example in learning situations where sensorimotor chunks are first learned separately before they are put together to form a single chain. This learning strategy, also known as part-whole learning (Park, Wilde & Shea, 2004), is seen, for example, in pianists learning a piece of music (Miklaszewski, 1989; Williamon, Valentine & Valentine, 2002). Whereas the end-effect of the chunks is reliably attained, the concatenation of two chunks to a single chain means introducing a further SRE-triplet. When this chain is first executed this effect will not be attained as reliable as the effects within the learned chunks and attention will be directed to the effect of this concatenating SRE-unit (see figure 2). If the effect is attained the rest of the chain "can rattle off" because it constitutes the initial condition for the second chunk. In this case usually actors will also become consciously aware of that nodalpoint, although the nodal point hypothesis makes no statement regarding consciousness and clearly assigns no function to it.

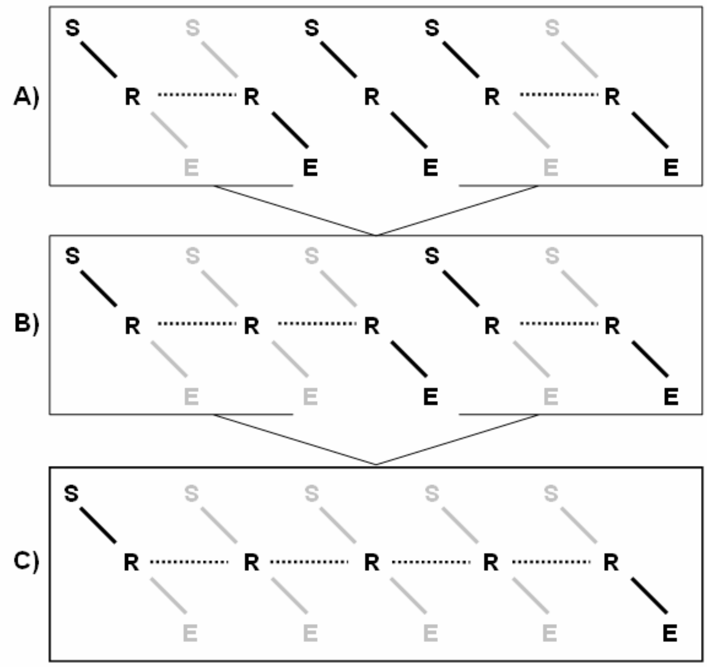

Figure 2. Concatenating two chains of SRE-triplets into one chain. This often means introducing a single SRE unit (A), of which the effect will - at least initially - not be reliably attained. A local uncertainty about continuation evolves (B) but disappears (C) after further learning.

Based on these assumptions the nodalpoint hypothesis makes predictions about what occurs if attention is directed towards the execution of a motor skill, either because of instructions or – as will be outlined in more detail below – as a result of "explicit monitoring" in a pressure situation. Firstly, the general idea allows translating "internal focus" and "explicit monitoring" into "attending to nodalpoints within a sensorimotor chain". Usually the movement (and therefore movement related intermediate effects) precedes the end-effect in the environment. Thus, focusing on the movement results in breaking up the chain into two chunks. The first part ends at the nodalpoint in focus and the second chunks starts with the initial conditions of this second sequence of SRE-triplets and ending with the overall end-effect of the sensorimotor chain (see figure 2). Secondly more precise predictions on an operational level are made that have two main features: (1) If attention is directed towards the execution of a motor skill than (a) higher muscular activity due to the "re-freezing" of the system through muscular co-contraction and (b) reduced exploitation of task properties, compared to the endpoint-control condition should occur. (2) Due to the underlying control structure, these effects should be expected only at a nodalpoint in focus. Thus rather than expecting global effects of an internal focus of attention, very specific effects at specific points in time are predicted (cf. Hossner & Ehrlenspiel, 2006).

Empirical evidence and open questions

Two studies have tested these predictions so far and both have used explicit instructions for focus of attention. In a first study (Hossner & Ehrlenspiel, 2006, Experiment 1; more detailed in Hossner, 2004) a laboratory task was used, in which participants learned to produce a sequence of 7 positions of a lever that was moved in three dimensions (push/pull, turn in/out, rotate inwards/outwards). After extensive learning (800 trials) participants entered the test phase. The test phase consisted of 8 blocks in which participants were asked to produce the learned sequence as fast and accurate as possible and were instructed to focus their attention on a particular position (blocks 2-7) or no focus instruction was given (blocks 1 and 8). The focus instructions were changed blockwise, the order was randomized between participants. Electromyographic data (surface electrode) of four muscles of the dominant arm was recorded. The electrical activity (EA) at the attainment of positions was calculated and z-score transformed to compute an index of muscular activity that could be pooled over muscles and compared between positions. Also the duration between attainments of positions was recorded and covariation (i.e. the correlation) between consecutive intervals calculated. After removing quadratic trends in the emg-data across blocks that were due to warming-up and fatigue-effects, muscular activity was found to be higher in the focus conditions than in the no-focus condition. More importantly, within the focus-conditions muscular activity was higher at a position, if that position was in focus compared to if it was not. For temporal data, a covariation between consecutive trials was found as evidenced by negative correlations between intervals. But as predicted by the nodalpoint hypothesis, these correlations were weaker between intervals where the position in-between was in focus compared to when it was not. These findings support the nodalpoint hypothesis in that higher muscular activity and reduced compensatory variability was found, but these effects were also found at specific points in time.

In a second study a more applied setting was used and also spatial rather than temporal compensation was investigated under focus conditions (Hossner & Ehrlenspiel, 2006, Exp.2; more detailed in Ehrlenspiel, 2001). Semi-professional basketball players were asked to shoot free-throw under four focus conditions. They were instructed to either "just shoot", to focus on the basket (= external focus), or to focus on one of two nodalpoints of the movement that were derived from individual phenomenological representation of the movement and referred to "ball over shoulder" and "ball leaves hand" positions within the movement. Surface EMG of four muscles of the throwing arm was recorded and electrical activity (EA) at the two nodalpoints computed. EA was again z-score transformed and an index of muscular activity over muscles was calculated so that muscular activity could be compared between nodalpoints and conditions. Kinematic data of four joints of the throwing arm was recorded with a highspeed camera. To evaluate spatial compensatory variability or covariation, a method developed by Müller and Sternad (2003) was used. First, the empirical dispersion of joint positions at the two nodalpoints across trials within a focus condition was calculated. Second, this was compared with a covariation free potential dispersion computed through a permutation method. Again as predicted by the nodalpoint hypothesis, higher muscular activity was found at a nodalpoint, if that nodalpoint was in focus compared to when it was not, independent of whether attention was directed to the other nodalpoint, the basket or no specific effect. Also, reduced spatial compensatory variability was found at a nodalpoint, if that nodalpoint was in focus, extending the findings obtained in the lever-sequencing task to the spatial domain.

Summarizing, the nodalpoint hypothesis of motor control (Hossner & Ehrlenspiel, 2006) assumes that sequences of SRE-triplets underlie the control structure of movements. Over the course of learning these single units are chunked to form chains of units. This formation of chains is accompanied by a shift from "controlling" (or attending to) single units to controlling the end-effect of the chain. If, however, the focus of attention is directed away from the end-effect to movement execution, this focus must be directed to the intermediate effects in the chain of effects. These intermediate effects are labeled nodalpoints. The focusing of nodalpoints results in increased muscular activity and reduced exploitation of task properties such as passive dynamics or compensatory variability.

Hossner and Ehrlenspiel (2006) identify three problems with the nodalpoint hypothesis. The first concerns the definitions and operationalization of the dependent variables thought to indicate "reduced exploitation". This problem is exemplified in the definition of the similar concept of "freezing of degrees of freedom": Different studies have used very different measures to indicate "freezing" but the validity of these different measures has not been tested. A second problem concerns the functional aspects of different focus of attention. So far, the nodalpoint hypothesis assumes that a focus of attention directed to the movement is non-functional and leads to performance decrement via reduced task exploitation and increased muscular activity. However, Kunde and Weigelt (2005, Exp. 3) have found performance enhancement under internal (movement directed) focus conditions, if the movement itself was the goal of the movement. The third and probably crucial problem refers to the definition of "nodalpoints". They are defined as "effects of elementary behavioral acts" but the question remains what these are – on a more implementational level of analysis. There are some suggestions for a more operational definition of nodalpoints that have not been tested, so far. First of all nodalpoints could be phases within a movement that show stability over repeated executions. More feasible could be phases within a movement where variations (or maybe even co-variations) across repetitions correlate with variance of the end-effect. This may be the case in interceptive tasks where variance of the impact may correlate with the result in the target. From a different point of analysis, nodalpoints may be phases within a movement that are phenomenally experienced and may be expressed verbally. As mentioned above, nodalpoints should exist at points within a movement where anticipated effects are not reliably obtained. Unexpected events or effects may lead to becoming aware of these events and the eventual perception of a nodalpoint. This idea was used in the basketball-study by Hossner and Ehrlenspiel (2006, Exp. 2). Participants were asked to explicitly describe their movements and mark prominent "points". These phenomenally experienced and explicitly verbalized points coincided with important points and phases put forward by basketball instructions (Niedlich, 1996). The problem is that phenomenal nodalpoints may not overlap with the underlying control structure of "behavioral" nodalpoints. Phenomenal nodalpoints then may resemble artificial nodalpoints! Hossner and Ehrlenspiel (2006) report a study by Todorov and Jordan (2001) that reveals this problem: In a hitting task they looked at the hand trajectory of both empirical and model data. Interestingly, although it had not been built into the optimal feedback control model, the strategy of moving back and forth was seen in both model and empirical data. Thus, although it plays no role in control of the task (hitting a ball) the backswing emerged. This backswing would most likely be seen as a nodal point by an observer and be reported from phenomenal experience by an actor. Therefore the focus instructions given in the basketball experiment by Hossner and Ehrlenspiel (2006) may have introduced artificial nodalpoints that were unrelated to the underlying control structure and focusing on these artificial nodalpoints may have had the detrimental effects observed. As Hossner and Ehrlenspiel (2006) point out, for further testing the nodalpoint hypothesis of motor control experimental conditions have to be found in which participants are implicitly lead to focus their attention to the execution of the movement. If expected changes in movement execution (muscular activity, task exploitation) occur at points in time of the movement, these points should be nodalpoints and the findings would provide more evidence for the nodalpoint hypothesis.

These experimental conditions that elicit a movement directed focus of attention may be the "pressure" situations that have been found to lead to choking. The following section will explain this idea in more detail.

Solving the Problem – Designing a Research Strategy

The question "Why do people choke under pressure?" was presented as the "heart" of this dissertation. Psychological research investigating the phenomenon of choking under pressure from very different perspectives was presented that first of all found a number of moderators that influence the direct relation between pressure and performance. In the analysis at the beginning of this chapter these moderators were assigned to lying either within the situation in which a task is performed, within the person that performs the task or within the task that is performed. Furthermore, research has also tried to identify mediators or processes that fall between the pressure situation and the performance result. Different theoretical approaches (e.g. drive-theories vs. attentional theories) have been used to explain these processes. Most support has been found for the attentional theories that assume that in a pressure situation attention is directed to the execution of the task which disrupts performance as a consequence.

The presented research as a whole may be seen as constituting a "research program" (Herrmann, 1994) within a domain (the choking-phenomenon). The analysis of this research program led to the conclusion that it has so far not been successful in explaining the (sensorimotor) mechanisms of the phenomenon. None of the theoretical approaches used to investigate the phenomenon so far have helped in clarifying the mechanism or solving this problem. This was defined as the cardinal problem of this dissertation. In the analysis it was therefore further concluded that other theories should be evaluated whether they may propose such a sensorimotor mechanism. The nodal-point hypothesis of motor control was then presented because it is assumed that this theoretical approach may indeed solve the question of the mechanism. As the next step in solving the cardinal problem (explaining a mechanism) a research strategy has to be designed.

Herrmann (1976) prescribes three stages to designing such a research strategy. First, core assumptions, based on the theories they are derived from, are formulated that are of rather abstract nature. These core assumptions are transformed into secondary assumptions through the help of additional assumptions. Secondary assumptions may also be labeled general research hypotheses because empirical or statistical hypotheses are derived from them. Additional assumptions refer to assumptions borrowed from other theoretical approaches, other empirical results or even plausibility. In order to design a research strategy for solving the cardinal problem – finding a mechanism behind choking – and before precise empirical hypotheses are formulated an attempt is taken to formalize this research strategy even further, based on the metatheory of science known as "structuralism" (Westermann, 2001; Willimczik, 2004). This will firstly be helpful in deriving general and empirical hypotheses from core and additional assumptions of the theoretical approaches applied. Secondly, it will be helpful in evaluating and interpreting of the results of this dissertation.

Developing a core assumption

According to Herrmann (1994) psychological research may be described in terms of "research programs". In structuralistic terms (Westermann, 2001, Hermann, 1994) such programs revolve around a "problem" which they try to solve and also some basic assumptions that refer to the theoretical elements, their relations and usually applicable research methods. It can now be postulated that the research on the phenomenon of choking under pressure as well as the research on the nodalpoint hypothesis both constitute research programs. Different types of programs within "fundamental" or "applied" science can be found, within the fundamental science "circumstantial" or "domain" problems are distinguished from "theoretic"- or "quasi-paradigmatic" research programs (Herrmann, 1994). The former apply theories to investigate a real, observable problem in order to explain it, the latter start from a theory to which a series of problems or phenomena is applied. Research on choking is clearly a circumstantial problem, because it tries to answer the question asked in the introduction: Why do people choke under pressure? The basic underlying assumptions of the "choking-program" can be expressed as:

> *"Situational factors such as a competition or the presence of an audience make a person want to perform well. This leads to pressure and consequently to choking."*

To fully represent the current status of the program some more elements concerning potential constraints may be added. Certainly the element of the attentional theories must be included:

> *"Pressure leads to explicit monitoring of the task, which leads to performance disruption and consequently to choking."*

These basic assumptions of the research program on choking under pressure may be given the (tentative) status of a theory (T_{CuP}; Herrmann, 1994).

Classification of the research on the nodalpoint hypothesis is more difficult: On the one hand movements, their control and their coordination are everyday problems, on the other hand nodalpoints and their theoretical basis as outlined may be of more academic origin – therefore research on the nodalpoint hypothesis may rather constitute a theoretic program. The basic assumption of this research program on the nodalpoint hypothesis (T_{NpH}) is that

> *"movements consist of a sequence of nodalpoints. Usually the end-effect or last nodalpoint 'controls' the movement but the focus may be shifted to intermediate nodalpoints. This leads to the disruption in the exploitation of task properties and to higher muscular activity at that nodalpoint and consequently to higher variance in the end-result."*

It is the strategy of circumstantial research programs to import theories from other programs to explain the problem it revolves around. This dissertation proposes that the nodalpoint hypothesis can be imported to the "choking-program" because it is able to further explain the problem. To import a theory, in this case T_{NpH}, the problem or the theory (here: T_{CuP}) has to be modified in such a way that it constitutes a partial model of T_{NpH}. Partial models of T_{NpH} can be described by using only terms that are not specific to T_{NpH} ("non- T_{NpH} -theoretic"). In the case of the nodalpoint hypothesis a partial model is any situation in which a movement is executed while the focus of attention is on the movement. Obviously, many situations could be found that meet these criteria. But usually theories declare – in structuralistic terms – „intended applications". That is they define classes of situations for which they assume that their assumptions are valid. If these situations can indeed be described in theory-specific (or „T-theoretic") terms, then they are called potential models of the theory T. A potential model of the nodalpoint hypothesis may be any situation in which the movement can be described as a sequence of nodalpoints and in which exploitation of task properties and muscular activity can be measured. These potential models are empirically tested and if valid, they become (true) models of the theory. To go back to importing the nodalpoint hypothesis into the „choking-program": the execution of a movement in a pressure situation can be thought to be a potential model of T_{NpH}. It can therefore be declared a further intended application and consequently be described in T_{NpH} (nodalpoint hypothesis-) theoretic terms as a potential model. This potential model is defined as the core assumption of this dissertation:

> *In a pressure situation, attention is directed towards nodalpoints of the movement executed. This leads to a „nodalpoint control", that can be evidenced by higher muscular activity and reduced exploitation of task proper-*

> *ties at the nodalpoints in focus. As a consequence performance breaks down.*

The importance but also charming nature of this formalization in structuralistic terms and the idea of „importing" the nodalpoint hypothesis to the research on choking under pressure can be explained by adapting Herrmann's phrasing (1994, p. 264): If the empirical testing of the potential model results in its acceptance as a (true) model, than there are two parallel consequences: (1) through the use of the nodalpoint hypothesis the phenomenon of choking can be better understood because a (sensorimotor) mechanism is described. (2) But also the nodalpoint hypothesis would have a further successful (and not only intended) application, thereby increasing its validity! However, if testing fails the consequence is not a falsification of T_{NpH}, the nodalpoint hypothesis, but only a loss of an intended application. And, of course, the cardinal problem (the search for a mechanism) would still be open. But because it was possible to describe the problem as a partial model of T_{NpH} at all, a failure would give hints at reformulating or modifying the partial model. This usually means adding further constraints.

Developing secondary assumptions

In order to transform the abstract core assumptions into testable secondary assumptions four explications and specifications have to be accomplished. First it must be noted that one part of the core assumption is not transformed because muscular activity is not evaluated in this dissertation. Recording and analyzing of EMG was renounced because the aim of this dissertation is to explain a mechanism behind choking, but not (primarily) to test the validity of the nodalpoint hypothesis. Of course a strong testing of the nodalpoint hypothesis would have to test the (strong) prediction of increased muscular activity at a nodalpoint in focus. But to find and explain a mechanism behind the phenomenon it is sufficient to show that the nodalpoint hypothesis can be applied to the problem.

Second, "pressure" has to be operationalized based on the definition given above. Research on choking has used many different ways of operationalization but in the current studies (e.g. Beilock & Carr, 2001) an artificial laboratory situation has been used with a fake competition in which participants were told that money was at stake depending on their performance. It is assumed that this manipulation is sufficient in producing "pressure" and will also used in this dissertation.

Third, it needs to be specified how performance is evaluated, including the exploitation of task properties. Performance is usually measured in extrinsic or environment-related task space. It then usually refers to the result of the task not the task execution – this is where choking manifests itself. It may be analyzed both quantitatively (as in number of holes putted in, number of errors, time taken…) or qualitatively (accuracy in the target). This level of analysis will be termed "overt performance". Some studies have looked beyond overt performance and have analyzed how the movement is executed (see above). This level of analysis will be termed "covert performance" and it is measured in intrinsic or body-related task space. It usually involves the analysis of the consistency of positions and changes of position over time of the effectors. A third level of analysis refers to the interaction of intrinsic and extrinsic variables and will be called "task exploitation". Bernstein (1967, p. 109) assumed that the highest stage of motor learning is reflected by "a degree of co-ordination at which the organism is not only unafraid of reactive phenomena in a system with many degrees of freedom, but is able to structure its movements so as to *utilize entirely the reactive phenomena* [sic] which arise". These reactive phenomena or task properties firstly include the mentioned functional or compensatory coupling of task variables. Therefore for measuring task exploitation, the covariation of movement parameters is the "paradigmatic" task property (e.g. Hossner & Ehrlenspiel, 2006). But another property of a task that can be utilized for efficient movement execution may be its dynamical stability properties. In fact, previous research results have found that dynamical stability may be exploited to produce stable performance and that the use of dynamical stability can indicate different control strategies (deRugy, Wei, Müller & Sternad, 2003). Analysis of dynamical stability, however, necessitates the use of continuous repetitive movements.

Fourth – and most crucial – the nodalpoints within a movement have to be defined that attention is directed to. This specification includes two separate problems: (1) As was mentioned above as a problem still to be solved within the nodalpoint hypothesis, it is not trivial to define nodalpoints of a movement. But (2) even if the nodalpoints of a movement are known, it is still not determined to which of these nodalpoints attention is directed to under pressure. Neither research on choking nor the nodalpoint hypothesis make a clear prediction on this issue. In order to meet this problem in this dissertation two approaches were adopted that led to the design of two studies. In Study 1, a "plausible assumption" is made about the nodalpoint in focus in that an interceptive task is investigated. It is certainly reasonable to "control" the impact of a racket with the ball that needs to be hit. Interestingly, there already exists a line of research that has found that indeed different movement control strategies can be detected through the analysis of parameters at ball-racket impact in a ball bouncing task (e.g. deRugy et al., 2003). Furthermore, this ball bouncing task is a continuous task, allowing the analysis of dynamical stability, it was therefore used in Study 2. On the other side, it is *experimentally* attempted to produce a "prominent" nodalpoint that can be assumed to be in focus under pressure. In the explication of the nodalpoint hypothesis it was laid out that a (prominent) nodalpoint develops when there is a relative uncertainty about the attainment of an effect. Such a relative or "local" uncertainty exists within a movement at the concatenation of two movement parts. Thus in Study 2 two partial movements or segments are first learned separately before they are concatenated. It is expected that under pressure the focus of attention should be directed to this concatenation. In this study a visuomotor tracking task was used.

In conclusion, the secondary assumptions for the two studies of this dissertation are phrased:

> S_1: A fake competition with financial incentives leads to "pressure" and consequently to decrements in overt performance (accuracy from target) in a continuous interceptive task (ball bouncing) as a result of reduced covert performance (movement timing) and task exploitation (reduced covariation of impact parameters and use of dynamical stability) due to an explicit monitoring of the task.
>
> S_2: A fake competition with financial incentives leads to "pressure" and consequently to decrements in overt performance (accuracy from target) in a continuous visuomotor tracking task as a result of reduced covert performance (movement timing) and task exploitation (reduced covariation between intervals) at a prominent nodalpoint due to an explicit monitoring of the task.

The transformation of these secondary assumptions or general hypotheses into empirical hypotheses will be described in detail in the experimental sections of this dissertation.

Study 1

Bouncing a Ball under Pressure –
Staying Tuned in Dynamical Stability

Study 1

The central question in the introduction of this dissertation – why did Roberto Baggio miss the goal – was not only generalized (Why do *people* choke under pressure?) but it was also specified in more detail: what are the processes involved in choking under pressure? The analyses of potential mediators did reveal that some ideas about rather cognitive processes exist and that a shift is postulated from automatic to controlled processing with a focus of attention directed to movement execution. This was called explicit monitoring. The analysis of current research further yielded that an explanation, however, was still missing for the cardinal question that seeks a mechanism on a sensorimotor level: How (and why) does explicit monitoring lead to the disruption of movements? In addition to a lack of theoretical work, also a lack of empirical work was observed that analyzes the performance (execution) rather than the result of a task. The nodalpoint hypothesis (Hossner & Ehrlenspiel, 2006) was then presented because it is assumed that it can provide for a mechanism behind explicit monitoring and subsequently the phenomenon of choking under pressure. Furthermore, the testing of the nodalpoint hypothesis implies investigating movement *execution*, i.e. the dynamics of the task.

Again, the nodalpoint hypothesis assumes that movements consist of a sequence of nodalpoints. Although usually the final end-effect of the task is in focus, attention may be directed to any of these nodalpoints – this leads to reduced exploitation of task properties at that nodalpoint. Thus there are two key predictions of the nodalpoint hypothesis as effects of explicit monitoring: (a) the reduced exploitation of task properties formulated on an operational level and (b) its time-referenced character, i.e. that these changes occur at certain (nodal-)points in time. The aim of Study 1 was to focus on the first of these two key features. A second aim of Study 1 was to extend the idea of task exploitation from the paradigmatic application – covariation or compensatory coupling of execution variables – to other properties of the task. One such property that can be utilized for efficient movement execution appears to be its dynamical stability properties.

Dynamical Systems and their Stability

One approach to understand and investigate human behavior is to conceive humans as biological systems and analyze their behavior in terms of system theory. In this sense a system emerges as the relationship of interdependent and regularly interacting parts or activities. Beyond that conception, humans and their performance can be viewed (and analyzed) as (complex) *dynamical* systems because the system evolves over time and this evolution is believed to follow some underlying dynamical rule (Jost, 2005). Evolution here does not refer to evolution in a phylogenetic sense but rather to a temporal process or a development. This transition or dynamical rule describes the development of the system as a sequence of states that the system is in. Because the transition between states depends on the actual state (and possibly even previous states) but not some external input, it is called dynamic. A typical example of a dynamic system is the evolution of populations: in a simple way it can be described completely by the initial size and the rates of reproduction and starving/dying. The evolution of dynamical systems and their transitional rules can be analyzed and modeled mathematically by using either discrete maps or continuous functions. For example, for the simple model of the evolution of a population, the logistic map has been found to adequately mathematically model this evolution (see for an introduction: Tufillaro, Abbott & Reilly, 1992): $x_{n+1}=rx_{\mathrm{n}}(1\text{-}x_n)$ where x_n is a number between zero and one that represents the state of the system (=size of the population in percent of the maximum population) at year n, and r is a positive number that represents the combined rate for reproduction and starvation (for example: $r=r_{\mathrm{rep}}/r_{\mathrm{starv}}$). With this mathematically exact description it is now possible to make predictions about future states of the system depending on the control parameter r. It is especially intriguing to evaluate when the system becomes stable, i.e. equilibrium is found. In mathematical terms the stability analysis of dynamical systems searches for attractors to which the system is asymptotically drawn, depending on the initial state of the system and the control parameters of the transition rule. Turning back to humans, behavior or performance can be seen as the evolution of a system over time. If so, then this behavior can be described in terms of a mathematical function. A classic example of the mathematical modeling of a motor task concerns the rhythmical movement of limbs, such as fingertips (Kelso, 1984, see for a model: Haken, Kelso & Bunz, 1985). If the fingertips are rhythmically oscillated left and right, this behavior can be described in terms of their relative phase, i.e. the position of the fingertips to each other within one movement cycle (back and forth). This system has been shown to have two attractors or stable states, that is when fingertips are either inphase-symmetric (tips both pointing out or both pointing in) or antiphase-parallel (tips point in the same direction). If this movement is started at some other phase it is drawn ("attracted") to either of the two states, although with increasing movement frequency, the inphase-symmetrical state is more stable (=attractive). It is important to note that "stable" does not mean "invariant" – stability must be conceived of as a region to which the system is drawn. If, for example, the system is disturbed away from its stable state, it eventually "relaxes" back to its stable state. If in the case of the fingertip oscillations the path of one finger is shortly obstructed, some odd phase (i.e. fingertip relation) will result, but very soon the fingertips will move again inphase. A last important note relates to the observation that this coordinated behavior of the fingertips passively arises from the system itself, it is not intentionally or actively controlled by the human actor! In fact, intentional voluntary control is needed to keep the system away from its attractors, although this is only possible to some degree.

Other and more complex movements and motor tasks such as interlimb coordination (Kelso & Jeka, 1992), juggling (Huys, Daffertshofer & Beek, 2003) or even eye-movements during reading (Engbert, Nuthmann, Richter & Kliegl, 2005) have been modeled as dynamical systems. And it has further been shown that learners not only have to discover the transition or dynamical rules but also their *exploitation* (Vereijken, Whiting & Beek, 1992). The exploitation of the system's dynamics, however, is impaired if parts of the system are restricted or "frozen" (see above). Consequently, if under pressure explicit monitoring occurs and this leads to a nodalpoint control, exploitation of task dynamics should be affected.

Utilizing dynamical stability: The ball bouncing task

Sternad and colleagues have extensively investigated a simple motor task in which dynamical stability and its exploitation plays a central role (e.g. Sternad, Duarte, Katsumata & Schaal, 2001). The task objective is to bounce a ball rhythmically, the actor holding a racket in his/her hand and hitting a ball into the air, trying to consistently hit a target height. Sensory information is required to adjust the racket's position and velocity when hitting the ball to achieve the desired target height. Feedback information may be used to correct for errors in performance. The cyclic ball-racket interactions have interested researches in areas such as robotics, mathematics, physics, and movement science. All attempts to physically and/or mathematically model the task have used a simplified one-dimensional version of the task, allowing only for up-and-down movements. The first models of the system's behavior had included closed-loop control as a necessary component for achieving stable behavior. Following classical control theory, Bühler, Koditschek and Kindlmann (1994) proposed a "mirror algorithm", in which the trajectories of the racket are planned and monitored based on information from the ball's trajectory. However, further analyses of the task revealed that this tight coupling between ball and actuator at every point in time is not necessary because it is the ball-racket impact which completely determines the ball's trajectory (given environmental restraints such as gravity). In addition, it was shown by a simple physical model, that dynamically stable solutions are exhibited by a ball bouncing on a planar surface, indicating that closed-loop control may not be necessary to produce stable behavior (Tuffilaro, Abbott & Reilly, 1992). In this applied mathematics literature the ball bouncing task has been modeled by a nonlinear discrete dynamical system, the ball bouncing map. The system can be described in terms of its performance, for example the height the ball was hit to. Stability analyses of the ball bouncing map are now interested in finding the order parameter colloquially put the variable on which the stability of the performance depends. This analysis reveals a stable period-1 attractor (i.e. a dynamical stable solution) when the table impacts the ball with a negative acceleration in an upward motion (for details see Dijkstra, Katsumata, de Rugy & Sternad, 2004).

In a series of experiments – using also a simplified, one-dimensional model – Sternad and colleagues were able to show that human actors are able to exploit this task inherent property to produce stable behavior. They observed stable performance when the racket impacted the ball with a negative acceleration while in an upward motion. In experiments closely copying the original physical model (Schaal, Atkeson & Sternad, 1996), using real (Sternad, Duarte, Katsumata & Schaal, 2001) or virtual (de Rugy, Wei, Müller & Sternad, 2003) rackets and balls they firstly showed that humans thus can perform the task by choosing the right acceleration. It is important to note, that the task in no way prescribes the use of negative acceleration. In fact, humans only learn to use (or utilize) this property over the course of learning the task (Sternad, Duarte, Katsumata & Schaal, 2000). Although this utilization appears to be computationally efficient, because it obviates error corrections, it is not energetically efficient (which it would be at zero acceleration because racket velocity is at a maximum). Using a virtual set-up, de Rugy et al. (2003) were secondly able to show that in addition to the "passive control" of the task (when negative acceleration is used) also more "active" strategies are used when (large) perturbations are applied to the system. It is the period of the racket cycle that is modulated to compensate for bounces that are too high or too low (see figure 4).

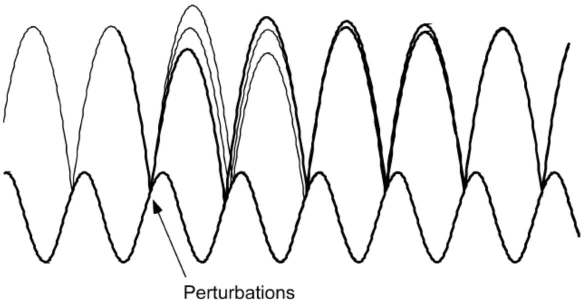

Figure 3: Idealized racket and ball trajectories: "Passive control" is evident after the second bounce because after small perturbations the system converges to steady state without active error correction (from deRugy et al., 2003, p.65).

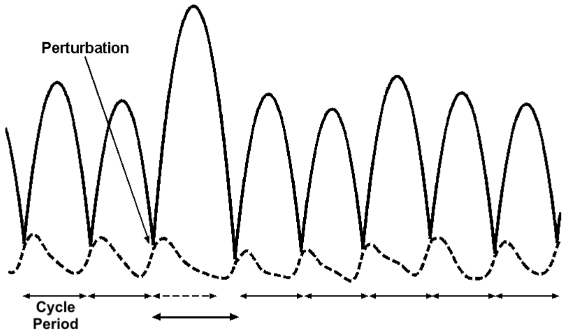

Figure 4: Real data from Experiment 1 exemplifying "active control". A large perturbation leading to an unexpected high bounce is corrected by a modulation of the racket period with a lengthened period.

In summary, in the task of bouncing a ball, human actors are able to (eventually) exploit dynamical stability of the system to produce stable performance. This "passive control" is indicated by negative acceleration of the racket at impact. However, more "active" control can also be present, which is indicated by modulations or variations of the racket cycle. Because different control strategies have been identified in which also dynamical stability is more or less exploited, this task appears to be excellent to address the cardinal question about processes underlying the choking phenomenon. The ball bouncing task was therefore used in Study 1.

Analysis of the ball bouncing task

The task of ball bouncing can be analyzed on three levels (see above): Overt performance, covert performance and task exploitation. Overt performance (the “result”-level) is measured by the absolute error of ball peaks from target height. Covert performance (the “execution”-level) is measured by the modulation of the cycle period. The cycle period can be defined as the interval between two successive impacts. The modulation of a cycle is then calculated by subtracting the period of the previous cycle from the actual cycle ($MOD=P_i-P_{i-1}$). Task exploitation is measured by the Acceleration at Impact of the racket (AC) and Covariation of impact parameters (COV). For calculating Covariation a randomization method proposed by Müller and Sternad (2003) can be applied. This method is based on the comparison between empirically measured variability in the result (V_{emp}) and covariation free variability (V_0). Covariation free variability is obtained by permuting data sets. Since ball height in this experimental set-up is completely determined by (1) the position of the ball, (2) the velocity of the ball and (3) the velocity of the racket at impact (see deRugy et al., 2003) these three parameters are permuted across impacts within one trial. For these permuted triplets the absolute error from target height is computed. To reduce chance effects, permutations are performed 1000 times and mean absolute error calculated to determine covariation free variability (V_0). Finally Covariation is calculated by $COV= (V_{emp}/V_0)-1$.

General Hypothesis for Study 1

Based on the assumptions that (a) psychological pressure leads to increased self-monitoring, i.e. a focus of attention directed to the movement or task, and that (b) this self-monitoring leads to nodalpoint control the general hypothesis for Study 1 was phrased as:

> S_1: A fake competition with financial incentives leads to “pressure” and consequently to decrements in overt performance (accuracy from target) in a continuous interceptive task (ball bouncing) as a result of reduced covert performance (movement timing) and task exploitation (reduced covariation of im-

pact parameters and use of dynamical stability) due to an explicit monitoring of the task.

With respect to the task of ball bouncing it can be expected that “under pressure” performers should show less utilization of negative acceleration at ball-racket impact and increased modulations (i.e. variability) of the racket period. Again, within the proposed levels of analysis the two variables fall on two different levels. Period modulation is an indicator of “covert performance” as it refers to the consistency of an execution variable. Racket acceleration, however, is an indicator of “task exploitation”, as it shows utilization of the properties of the dynamical system.

Experiment 1

A specific feature of dynamical stability is that if the system is perturbed away from its stable state it relaxes back to that stable state, at least if the perturbation is not to large (Jost, 2005). Relaxation is a purely “passive” process which makes use of the stability properties. This property allows for an extension of the hypothesis formulated above: In “pressure situations” relaxation after perturbation should be prolonged because the passive relaxation is interfered with through active strategies. Thus in Experiment 1 perturbations were introduced to the system and the time was analyzed that was used for the system to relax back to a steady state after perturbation.

Methods

Participants

25 undergraduate students (10 male, 15 female, age 20 - 28 years) were recruited as participants. Data of two participants had to be discarded because one participant did not appear for the second session, and the data of another participant had missing or obscure data. Participants received extra credit for an undergraduate class as compensation for participation and were given the $10 as set as a reward in the competition (see below). The participants were informed about the experimental procedure and prior to participation signed the consent form in compliance with the Regulatory Committee of the Pennsylvania State University.

Apparatus and material

A virtual reality set-up was used in which the participant manipulated a real table-tennis racket to bounce a virtual ball rhythmically to a target height. As in the previous studies (e.g. deRugy et al., 2003), ball and racket displacement was restricted to one dimension. Participants were positioned in front of a large back-projection screen onto which the visual display (1.8 m wide and 1.33 m high) was projected. The display consisted of a red horizontal line from the left edge to the middle of the screen (the target line) and a magenta rectangle (the paddle, length: 0.2 m, width: 0.02 m) in the middle of the screen (Figure 2). The target line was displayed at a height of 2.0 m (length: 0.9 m, width: 0.02 m), the paddle's minimum position was 1.2 m off the floor. The ball was displayed as a yellow filled circle, 0.06 m in diameter. The participant stood upright at a distance of 1 m from the screen and held the racket horizontally at a comfortable height. A rigid rod with three hinge joints and one swivel joint was attached to the racket surface and ran through a noose that was part of a heavy weight floor piece. The material of the rod and the noose minimized friction. The joints allowed the racket to be moved and tilted freely in three dimensions although only up-and-down movement of the rod was recorded and displayed. By its vertical motion the rod rotated a wheel. The revolutions of this wheel were measured by an optical encoder and the signal from the optical encoder was transformed by a digital board and sent online to the PC that controlled the virtual display. This projection onto the screen was in real time with a minimum of time delay. The gain between displacement of the real and virtual racket was 1. Acceleration of the racket was measured with an accelerometer attached to the paddle above the rod. Data sampling frequency was set to a maximum of about 850Hz which averaged to 400 Hz. In order to simulate the impact of the racket and the virtual ball, a mechanical brake was attached to the rod. The brake was activated by a solenoid which in turn was triggered by the software controlling the interactive display. The trigger was started at 15 ms before estimated actual (i.e. visual) impact time. Impact time was estimated by using the distance between racket and ball divided by the relative velocity between them at that moment. The brake was applied at each impact for a duration of 30 ms. The electronic delay due to computations had a duration of only one sampling interval. The mechanical delay between the control signal and the onset of the brake was approximately 10 ms. The force developed by this brake was adjusted to that produced by a tennis ball falling on the racket, it was approximately constant for all contacts.

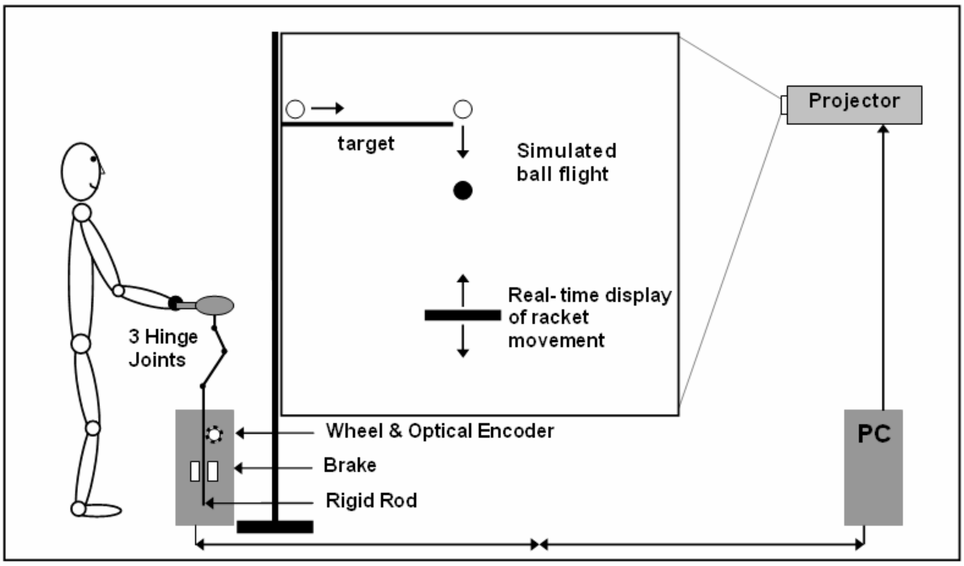

Figure 5. Semi-virtual set-up of the ball bouncing task. Participants were positioned in front of a screen and moved a racket. The ball as well as a display of the racket was projected onto the screen. Task objective was to hit the ball rhythmically and accurately to the target line.

Custom-written software computed the ball trajectories online based on the measured racket movements and the contact parameters of ball and racket. The simulated ball trajectories were projected onto the screen so that the subject only interacted virtually with the ball (Open GL Graphics). The visual display was calculated every 3 ms, based on the acquisition rate set to maximum sampling rate with an average of 400Hz. This visual display was projected to the screen with an update rate of 60 Hz, due to limitations of the projector. The ball's trajectory was calculated using the equations of ballistic flight and inelastic instantaneous impact. Whenever the ball was in the air, its vertical motion was only influenced by gravity and its ballistic flight was described by

$$x_B = -1/2 g t^2 + \dot{x}_{B,0} t + x_{B,0} \tag{1}$$

where x_B is the vertical position of the ball, g is gravity, and $x_{B,0}$ and $\dot{x}_{B,0}$ are the initial position and velocity of the ball. As the ball's flight trajectory was calculated between two contacts, $\dot{x}_{B,0}$ was determined by the impact relation

$$\left(\dot{x}_B^+ - \dot{x}_R\right) = -\alpha\left(\dot{x}_B^- - \dot{x}_R\right) \tag{2}$$

where $\dot{x}_B^-$ and $\dot{x}_B^+$ denote the velocity of the ball immediately before and after the contact, respectively. $\dot{x}_R$ denotes the velocity of the racket at impact, assuming instantaneous impact. The coefficient of restitution α captures the energy loss at impact. The elastic impact described in Equation 2 assumed that the mass of the racket was sufficiently larger than the mass of the ball so that the effect of the impact on the racket trajectory could be ignored. $x_{B,0}$ in Equation 1 was given by the position of the impact measured in extrinsic coordinates.

Procedure and experimental conditions

After the participants were positioned in front of the screen they were given details about the task, specifically they were asked to rhythmically and accurately hit the ball to the target line. They were advised that when the trial started it was helpful to actively approach the first falling ball before it hit the paddle. No further specific instructions about how to perform the task were given. The experiment consisted of a Practice and a Performance Session scheduled on two days; most participants appeared for the second session within 24 hours. In the Practice Session, participants completed 32 trials with short rests after trials 8, 16 and 24. Each trial lasted 40 s which allowed for 50 to 60 bounces, depending on the ball amplitude. Immediately after each trial, information about the score was presented on the screen. It gave the absolute error (in cm) of the ball height to the target line across all bounces of the trial. Participants were informed that this number represented the average deviation from the target and that over practice, they should reduce this number. A fading procedure was applied to this performance feedback. The score displayed always only related to the last trial. There was a five-second break between successive trials. The last 8 trials in the Practice Session constituted a Practice Test in which perturbations were introduced to the coefficient of restitution α at every eighth impact. The coefficient α was changed randomly between limits at these impacts resulting in unexpected bounces of the ball. To obtain sufficiently large perturbations, the perturbed coefficient of restitution (αP) was set to be different from its normal value (α= 0.5) by at least 0.10. To prevent too large perturbations, the maxi-mum difference from the normal value was set to 0.20. Hence, αP was randomly determined for each perturbed impact within the ranges $0.3 \le \alpha P(low) \le 0.4$ and $0.6 \le \alpha P(high) \le 0.7$. Previous studies had shown that participants need an average of 5 cycles to get back into a steady state after perturbations (deRugy et al, 2003). With the aim to allow all participants to resume a stable rhythm after a perturbation this interval of 7 bounces between perturbations was chosen.

The Performance Session consisted of three warm-up trials, a Baseline Test and a final Performance Test. Each test in the Performance Session consisted of 12 trials of 40 s. no performance feedback was given after trials. After the Baseline Test participants were further assigned to a High-Stress (12 participants) or No-Stress Group (11 participants). For the High-Stress Group a manipulation was used that uses four features to increase "psychological pressure" and has become a standard in research investigating choking under pressure (Beilock & Carr, 2002; Gray, 2004). Participants received a sheet explaining to them that (1) they were to enter a competition for which they were teamed with another participant of this study. If both team-mates could raise their performance by 25% final Performance Test compared to their individual average performance in the Baseline Test, each would be rewarded $10. (2) However, if one of them could not raise his or her performance, the other would not receive the reward either. (3) Furthermore they were told that a list of the teams with results and potential rewards would be openly posted after the experiment. (4) Just prior to starting the first trial of the Performance Test participants were verbally told that their team-mate had already successfully raised his/her performance by 25%. Participants were always told that they had been teamed up with a participant of the opposite sex. After the experiment participants were given a debriefing statement, explaining them that every participant would receive $10, independent of their's or others' performance.

Participants filled out the State-Trait-Anxiety Inventory (STAI, Spielberger, Gorsuch & Lushene, 1970) after 6 trials in the Baseline and in the Performance Test, respectively. Upon completion of the last trial, participants were given a debriefing statement and participants in the High-Stress group were asked whether they had been convinced that they had entered a competition.

Data reduction and analyses

The raw data of racket displacement were filtered with a Savitzky-Golay-filter, racket acceleration was taken from Savitzky-Golay filtered online-recordings of the accelerometer. This procedure included interpolating data to a constant sampling frequency of 500Hz. To remove outliers, the data at the impacts were analyzed trial by trial and outliers greater than 2 standard deviations from the mean of the respective trial were deleted before calculating means across bounces and then trials.

The variable of interest in this experiment was how long it takes participants to return their performance to a steady state performance after a perturbation to the coefficient of restitution of the ball at ball-racket impact. To this end first the data in each of the perturbed trials was segmented into pieces of eight bounces, the first being the perturbed bounce. This data was then divided into bounces following an αP(low) or an αP(high). For these two groups of data, mean performance per bounce was computed for the Practice, Baseline and the Performance Test, respectively. To estimate the return of performance after perturbation, for each participant, Test and variable, an exponential function of the type $f(x)=a+b*e^{-cx}$ was fitted to the performance of the 8 bounces in each of the four variables, separately for αP(low) and αP(high) – for an example see figure 6. "Steady state performance" was defined by (a) the mean performance across the last three bounces separately for each participant, Test, αP-condition and variable and (b) by confidential limits around this mean. Confidential limits of steady state performance, were defined by the between trial standard deviation of performance across trials 19 to 24 of the Practice Phase of each variable. To calculate the time to return to steady state, instead of simply taking the first bounce which was within confidential limits of steady state performance, the intercepts between confidential limits and the return function were defined as the exact return to steady state and labeled τ (see figure 6).

Empirical hypothesis eH_{11}

Based on the secondary assumption or general hypothesis S_1 the empirical hypothesis can now be phrased (Herrmann, 1994):

> eH_{11}: In the ball bouncing task a fake competition with financial incentives leads to "pressure" (increase in state anxiety) and consequently to decrements in overall overt performance (Absolute Error from target), as a result of prolonged relaxation to steady state (τ) in overt performance (Absolute Error from target), covert performance (period modulation) and task exploitation (covariation of impact parameters and negative racket acceleration at impact).

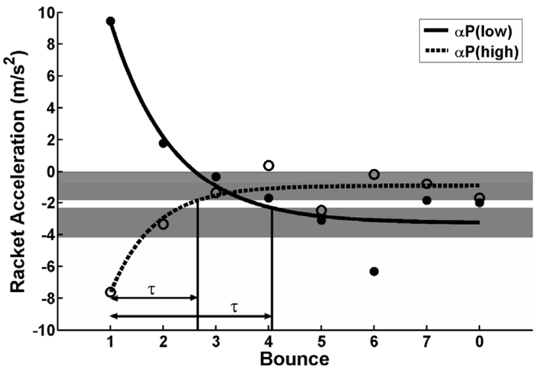

Figure 6. Defining "time to return to steady state (τ)" This figure displays single subject data for Racket Acceleration. Mean values for each bounce across trials of each Test were computed, separate for low and high perturbed coefficient of restitution αP. Then exponential functions were fitted to the data. Steady state was defined by the mean across the last three bounces, with confidence limits derived from standard deviation around the mean in the (unperturbed) trials 19-24 (grey area). The intercept between confidence area of steady state and return functions was defined as the "time to return to steady state (τ)".

Results

Practice Session

The Practice Session consisted of two parts: During the first 24 trials participants had the chance to learn the task without perturbations. Accuracy and consistency across bounces in one trial of overt and covert performance were analyzed as well as Task exploitation. Beginning with trial 25, perturbations of random size were applied to the coefficient of restitution every 8th bounce, resulting in somewhat unpredictable ball trajectories. Here, performance across bounces was not further evaluated, only accuracy and consistency across the last bounces before perturbation were evaluated.

Performance measures

For the Practice Session an exponential decay was expected for all the measures indicating learning. Thus an exponential function of the type $f(x)=a+b*e^{-cx}$ was fitted to each subject's data across the first 24 trials of learning. Figures 7- 9 display scatter plots of the individual performances for all trials. Absolute Error, Period Modulation and Acceleration decreased exponentially across trials of learning but not Covariation. Based on visual inspection of raw data a linear fit of the type $f(x)=a+bx$ was applied to Covariation data. Participants appear to exploit Covariation from the beginning.

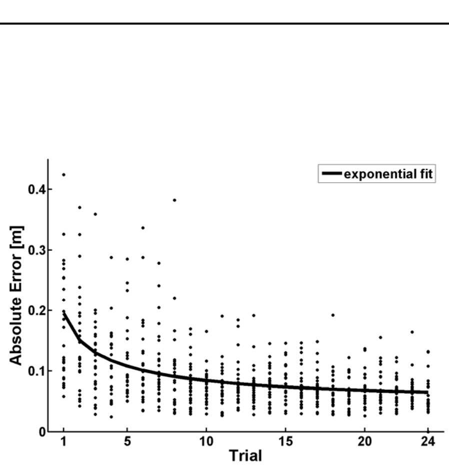

Figure 7. Overt Performance: Scatterplot (individual data) and mean fitted values of Absolute Error from target height in each of the first 24 trials of the Practice Session.

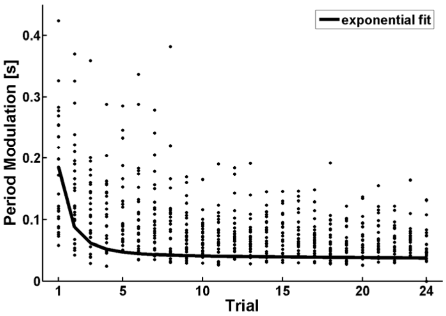

Figure 8. Covert Performance: Scatterplot (individual data) and mean fitted values of Period Modulation in each of the first 24 trials of the Practice Session.

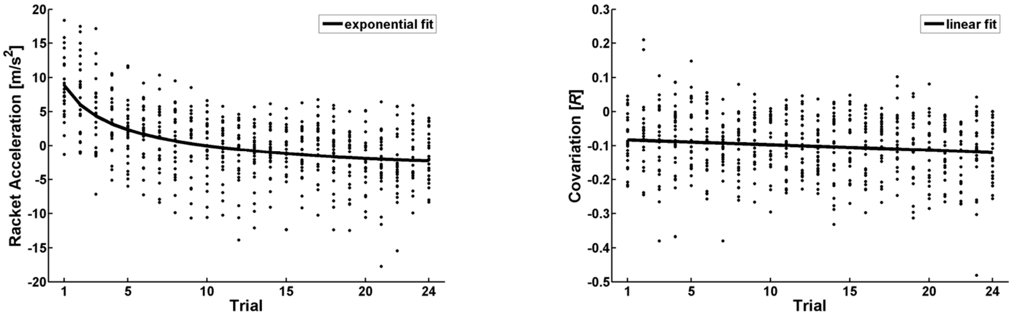

Figure 9. Task exploitation: Scatterplot (individual data) and mean fitted values of Racket Acceleration (left) and Covariation (right) in each of the first 24 trials of the Practice Session.

Relaxation to steady state performance after Perturbation

The return after perturbation of all the measures in the last 8 trials of the Practice Session was only analyzed visually. As can be seen in figures 10- 12 participants' performance in all variables quickly relaxed back to a steady-state performance after perturbation (bounce "0").

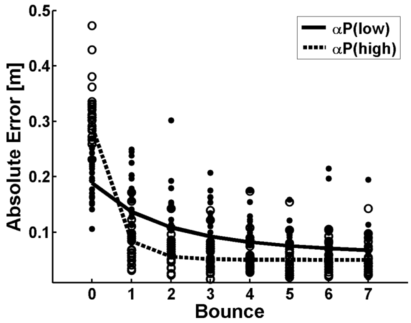

Figure 10. Overt performance: Scatterplots of subjects' mean Absolute Error across bounces and respective mean fitted values in the last 8 trials of the Practice Session. Bounce 0 was perturbed.

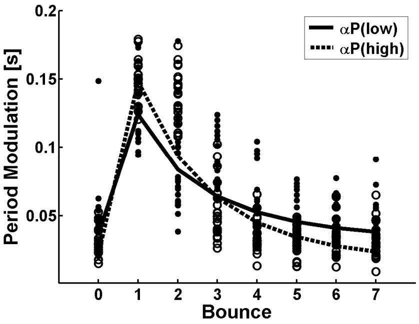

Figure 11. Covert performance: Scatterplots of subjects' mean Period Modulation across bounces and respective mean fitted values in the last 8 trials of the Practice Session. Bounce 0 was perturbed.

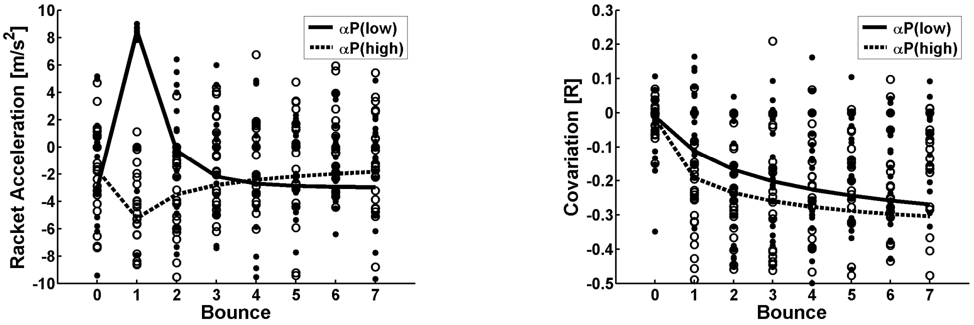

Figure 12. Task exploitation: Scatterplots of subjects' mean Racket Acceleration (left), and Covariation (right) across bounces and respective mean fitted values in the last 8 trials of the Practice Session. Bounce 0 was perturbed.

Performance Session

Manipulation Checks

In order to assess the effectiveness of the pressure manipulation two measures were analyzed. First, the change in level of state anxiety between Baseline and Performance Test was compared. As Table 1 indicates, an increased level of anxiety in the High Stress group was found before the Performance Test ($F(1,21)=13.83$, $p<.05$, $f=0.81$). Secondly, it was analyzed, whether participants in the High Stress group were convinced they had entered a true competition. 5 participants were completely convinced, 4 appeared to have some doubts, 1 was quite doubtful and 2 did not believe it at all. Although the pressure manipulation may not have been successful with the latter 3 their data was not excluded from analysis because they showed increases in the state-anxiety level between 7 to 10 points.

Table 1. *Means and standard deviations of STAI-state scores.*

	Test	
Group	Baseline	Performance
No Stress	27.64 ± 5.63	28.09 ± 5.72
High Stress	33.42 ± 9.00	41.58 ± 11.11

Performance measures

To evaluate overall performance in the Performance Session, a 2 (Groups) x 2 (Tests) ANOVA with repeated measures on the second factor was computed. Participants in the High-Stress group were able to increase their accuracy in hitting the target line across all bounces (perturbed and unperturbed) significantly more than participants in the No-Stress group (Interaction Group x Test: *F*(1,21)=4.35, *p*<.05, *f*=0.46). The main effect of difference between groups was not significant (*F*(1,21)=1.45, *p*>.05, *f*=0.26) and there was also no significant difference between groups in the Baseline Test (*F*(1,21)=1.99, *p*>.05, *f*=0.31).

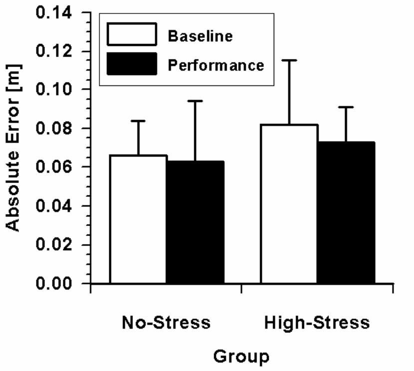

Figure 13. Overall overt performance in the Performance Session: Absolute Error from target height.

It was further evaluated, whether it would be worth analyzing only participants that performed worse under pressure. But only 1 participant in the High-Stress Group and 3 in the No-Stress Group showed performance decrement. Also the correlations between anxiety scores and Absolute Errors were examined. To this end, first difference scores between Baseline Test and Performance Test were computed. For the No-Stress Group a non-significant positive correlation of *r*=.04 was found, for the High-Stress Group a non-significant negative correlation of *r*=-.02. Further inspection of the High-Stress Group interestingly found a significant quadratic regression (F(8)=4.47, p<.05; $f(x)=0.004-0.0035*x+0.0002*x^2$).

Relaxation to steady state performance after Perturbation

To evaluate relaxation time 2 (Groups) x 2 (Tests) x 2 (size of αP) ANOVAs with repeated measures on the last two factors were computed for each of the four variables. Figure 14 displays relaxation time to return to steady state (τ), differentiating between perturbed coefficients of restitution lower and higher than normal (αP(low) vs. αP(high)). Relaxation time to steady state for the Absolute Error was faster in the Performance Test than in the Baseline Test (main effect Test: *F*(1,21)=8.16, *p*<.05, *f*=0.62), but no significant interaction effects were found between Experimental Groups and Tests (*F*(1,21)=0.50, *p*>.05, *f*=0.15) or Groups, Tests and size of αP (*F*(1,21)=0.22, *p*>.05, *f*=0.10).

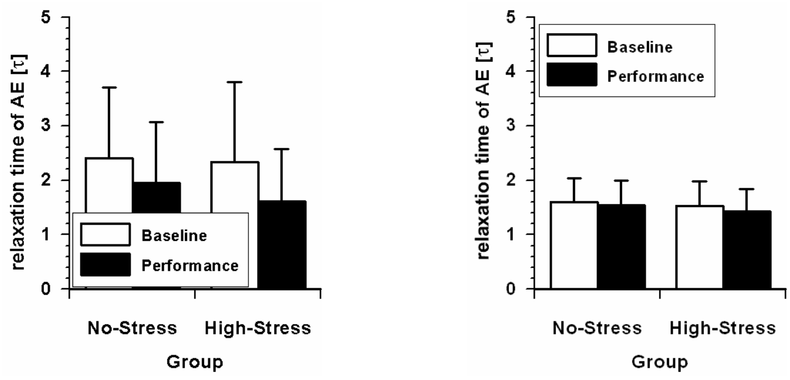

Figure 14. Relaxation time to steady state overt performance in the Performance Session for Absolute Error from target height after perturbed bounces unexpectedly too low (left) or too high (right).

No significant effects were found for the relaxation time of Period Modulation (figure 15). Relaxation time was not significantly faster in the Performance Test than in the Baseline Test (*F*(1,21)=0.47, *p*>.05, *f*=0.15), and there were also no significant interaction effects between Experimental Groups and Tests (*F*(1,21)=0.41, *p*>.05, *f*=0.14) nor between Groups, Tests and size of αP (*F*(1,21)=2.02, *p*>.05, *f*=0.31).

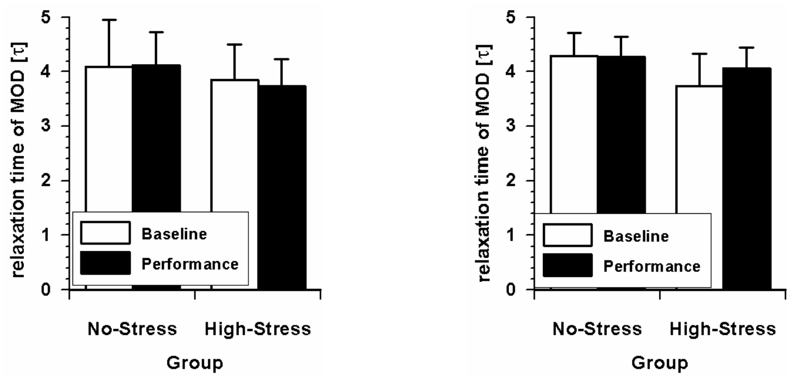

Figure 15. Relaxation to steady state covert performance in the Performance Session: Period Modulation after perturbed bounces unexpectedly too low (left) or too high (right).

Relaxation time for Acceleration at Impact (see figure 16) was significantly faster for the High-Stress Group than for the No-Stress Group in the Performance Test (Interaction Groups x Test: $F(1,21)=5.20, p<.05, f=0.50$). There was significant main effect of Test ($F(1,21)=5.66$, $p<.05$, $f=0.52$) but not a significant 3-way interaction between Groups, Test and αP ($F(1,21)=1.55, p>.05, f=0.27$). Although from figure 17 it appears as participants in the High-Stress Group are faster to relax to steady state Covariation in the Performance Test than participants in the No-Stress Group, there was no significant interaction (Interaction Groups x Test: $F(1,21)=2.87$, $p>.05$, $f=0.37$); Interaction Groups x Test x αP: $F(1,21)=0.67$, $p>.05$, $f=0.18$) nor main effect of Test ($F(1,21)=0.05, p>.05, f=0.04$).

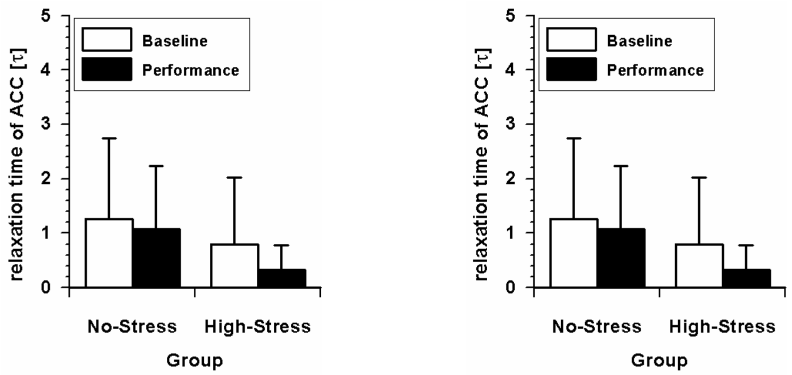

Figure 16. Relaxation time to steady state task exploitation in the Performance Session: Acceleration at Impact after perturbed bounces unexpectedly too low (left) or too high (right).

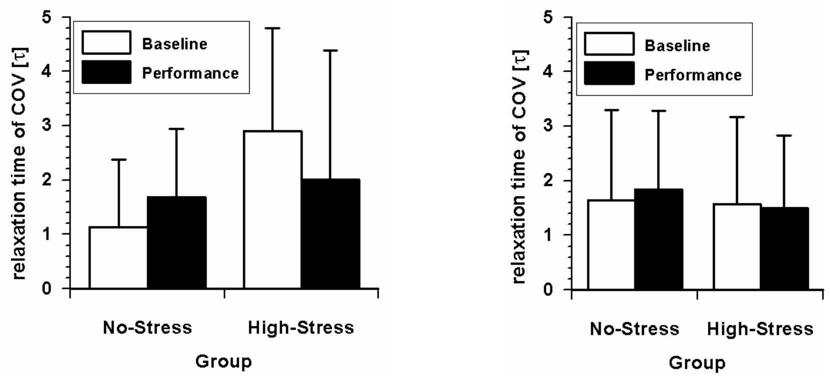

Figure 17. Relaxation time to steady state task exploitation in the Performance Session for Covariation after perturbed bounces unexpectedly too low (left) or too high (right).

Discussion

Based on the assumptions that (a) psychological pressure leads to "choking", and that (b) this "choking" occurs because performers focus their attention on the execution of a motor skill in such situations predictions of the nodalpoint hypothesis (Hossner & Ehrlenspiel, 2006) can be tested. It states that the exploitation of task properties is reduced when actors focus their attention on the execution of a motor skill. Specifically for the task of ball bouncing it was be expected that a fake competition should lead to poor performance and that it should take performers longer to relax to steady state performance after perturbations because of reduced task exploitation. However, results in Experiment 1 show that participants did not choke under pressure, although they did experience pressure. Instead, participants in the fake competition were able to reduce their error scores and thus raise their performance whereas participants in the non-stressed group were not. This overall enhanced performance is only partially accompanied by a faster relaxation to steady state after perturbations. Neither relaxation time of Absolute Error nor of Period Modulation, which measure overt and covert performance, respectively, is affected by the pressure manipulation. Interestingly, relaxation time of Acceleration at Impact and of Covariation (although not significantly) is faster in the pressure situation, a finding that is completely contrary to the original hypothesis.

The formalized approach by Herrmann (1976, see introduction) clarifies that the transformation-process from a theory into an empirical study consists of four steps: the specification of core assumptions, the development of secondary assumption through the use of additional assumptions, the subsequent proposal of empirical hypotheses and finally the empirical study. If now the empirical hypothesis is not confirmed the question arises what point in the transformation process needs to be analyzed in detail and potentially modified. It is of course appropriate to not start with the core assumption but with the last step.

Thus, methodological problems that lie in designing and conducting the experiment will be investigated first. Looking at overt performance it can be argued that a "floor-effect" is the reason that the No-Stress Group did not decrease in Absolute Error (fig. 13). The Stress Group then only approaches that "floor" level of performance. Although the difference between Groups at the Baseline Test is not significant, given the small power ($1-\beta=0.29$) due to the comparatively small sample, it could thus be argued that the matching of the groups was not successful. Clearly, a laboratory situation will never be comparable to real-life situation wrought with psychological pressure, such as a soccer world-cup final for example. From an experimental viewpoint, it may thus be that the participants did not feel under pressure in the fake competition and therefore did not choke. Three factors indicate, however, that the pressure manipulation must have been effective – at least as any measure in an internal valid experimental set-up can be. First of all, the manipulation applied has been used by many researchers before with samples from the university student population and has been shown to be effective in leading to "choking under pressure" (e.g. Beilock & Carr, 2001). Second, most of the participants in the Stress Group were convinced that they entered a true competition. Third and most importantly, analyses of the levels of state-anxiety clearly show that anxiety increased in the fake competition, indicating that participants in the Stress Group did feel "under pressure".

Analyzing the preceding step in the formation-process, the secondary assumptions or general hypotheses, it must be asked whether the pressure situation actually lead to "explicit monitoring". If this was not the case, the core assumption would have to be modified. With improved performance under pressure in this experiment it may indeed be questioned whether the increased "pressure" resulted in explicit monitoring. If this was not the case than the experimental situation did not even pose an intended application to the nodalpoint hypothesis! There are two possible explanations why increased "pressure" may not have resulted in explicit monitoring. First, Masters (1992, 2000) has proposed the "reinvestment-hypothesis" which states that only if explicit task knowledge is accrued in the course of learning, this knowledge can be "re-invested" under pressure. Accordingly in his experiments he found that participants who had learned implicitly did not choke under pressure. Transferred to the task of ball bouncing in this experiment, participants may not have "known" very much about how they were performing the skill, especially since they were not provided with any instructions. Without explicit knowledge there may not have been "explicit monitoring". Second and alternatively, it could be that the task of bouncing a ball does not promote explicit monitoring. If participants, for example, detect that stable performance results from negative racket acceleration at impact even increased psychological pressure may not lead them to change strategies.

In this experiment it was not evaluated whether explicit monitoring occurred, but rather taken as granted (since it was a core assumption!). Hence there is not enough empirical evidence that could warrant a modification of the core assumptions. Consequently, a second experiment was designed to address this issue. If participants receive explicit instructions during learning they should accrue explicit knowledge which should be “reinvested” under pressure. This should than lead to “choking”. Also the methodological problem with the possible floor effect was addressed.

Experiment 2

Although the nodalpoint hypothesis of motor control (Hossner & Ehrlenspiel, 2006) makes no statement regarding consciousness or subjective awareness of nodalpoints, in the Discussion of Experiment 1 it was argued that explicit monitoring may depend on the amount of verbalizable explicit knowledge. This notion is based on research by Masters (1992, Liao & Master, 2002) who found explicit monitoring under stress in participants who had received explicit instructions during learning. Therefore, half of the participants in Experiment 2 were provided with explicit instructions how to learn and execute the task. Second, to evaluate whether explicit monitoring occurs at all, an attempt was made to assess whether participants focus their attention on the movement execution. To this aim a tone-judgment task was introduced which was effectively used by Gray (2004) to evaluate the focus of attention. Furthermore, participants' explicit knowledge was evaluated by asking them to write down list rules that they would teach others to easily perform the task.

Methods

Participants

48 undergraduate students (19 male, 29 female, age 18 - 23 years) were recruited as participants, none of whom had participated in Experiment 1. Data of 9 participants had to be discarded because some participants did not appear for the second session (5), others did not show stable behavior at the end of the Practice Session (4). Participants received extra credit for an undergraduate class as compensation for participation and were given the $10 offered in the competition (see below). The participants were informed about the experimental procedure and prior to participation signed the consent form in compliance with the Regulatory Committee of the Pennsylvania State University.

Apparatus and material

The same virtual set up as in Experiment 1 was used with two changes made. This time no perturbations were introduced and only stable performance was assessed. In addition, a tone judgment task using a prompting-technique developed by Gray (2004) was applied to test the focus of attention of participants. A tone of 80 ms duration was presented after 34 s of a trial. This tone was either high-pitched (550 Hz) or low-pitched (450 Hz), with tone-pitches presented in a random sequence across trials. After the completion of each trial participants were verbally given a prompt randomly chosen from 3 options: “direction”, “pitch” or no prompt. As response to the “direction” prompt participants had to tell the direction of the travel of the arm while the tone occurred, i.e. during an upward or downward movement of the arm. The response to the “pitch” prompt was to tell whether the tone presented was the high- or the low-pitched tone. When no prompt was given, participants were instructed that no response was required. The prompt was chosen randomly from the three options (“direction”, “pitch” or no prompt), constrained only by the ratio of 3: 3: 2 during the Practice Session and the ratio of 4: 3: 3 during the Performance Session.

Procedure and Experimental Conditions

The design was similar to Experiment 1 and consisted of a Practice Session on day 1 and a Performance Session on day 2. Most participants appeared for the Performance Session within 24 hours following the Practice Session. The Practice Session in Experiment 2 consisted of 32 trials each lasting 40s with short rests after trials 8, 16 and 24. Performance feedback (Absolute Error from the target height) was presented on the screen after a trial. The same fading procedure as in Experiment 1 was applied reducing feedback frequency from initially every single trial to eight trials at the end. Beginning with trial 9, participants were presented the tones during the trials and the prompts after the trials. In each of these trials one of the three prompts was given, resulting in 9 “pitch” and “direction” prompts and 6 trials with no prompts presented.

After the first 4 trials of the Practice Session, participants were assigned to one of two groups, either the “No-Instruction Group” or the “Instruction Group”. Groups were matched based on their average performance (absolute error) in these four trials. Participants in the No-Instruction Group served as a control group and were not given any instructions on specifics of their performance. Participants assigned to the “Instruction Group” were given a set of 3 instructions intended to encourage them to attend to their movements, i.e. use an internal focus of attention. The following instructions were given consecutively before trials 5, 7 and 9. Participants were asked to openly recall these three strategies before trials 17 and 25 of the Learning Session and were also reminded to use them to improve in the skill.

> “Assume an upright posture and position yourself in a way that you can move the paddle directly above the rod and the apparatus! The main

> movement is in the elbow. So try to mainly move your arm up and down but still try to keep the wrist flexible!"
>
> "Try to find a constant range of motion of your arm, so that your arm always travels the same distance or amplitude on every bounce."
>
> "Within that constant range of motion you also want to move in a smooth and steady up-and-down fashion."

To evaluate the accrual of explicit knowledge about the task, upon completion of the last trial of the Practice Session, participants were asked to write down (question 1) what advice they would give other participants in order to learn the task fast and (question 2) what they thought which specific action lead to stable performance.

The Performance Session on day 2 consisted of 3 warm-up trials, a Baseline Test and a final Performance Test. Each test in the Performance Session consisted of 10 trials, of 40 s duration each; no performance feedback was given after the trials. After the Baseline Test the two Instruction Groups were further divided into a High-Stress and a No-Stress Group. The No-Stress Groups received no further instructions or manipulations and the High-Stress groups received the same pressure manipulation as the group in Experiments 1. To evaluate the level of anxiety, participants filled out the State-Trait-Anxiety Inventory (STAI, Spielberger, Gorsuch & Lushene, 1970) before the Baseline and Performance Test. Upon completion of the last trial, participants were given a debriefing statement and participants in the High-Stress group were asked whether they had been convinced that they had entered a competition.

Empirical hypothesis eH_{12}

Based on the secondary assumption or general hypothesis S_1 the main empirical hypothesis for experiment 2 can now be phrased (Herrmann, 1994):

> eH_{12}: In the ball bouncing task a fake competition with financial incentives leads to "pressure" (increase in state anxiety) and consequently to decrements in overt performance (Absolute Error from target), as a result of reduced covert performance (period modulation) and task exploitation (covariation of impact parameters and negative racket acceleration at impact) in subjects who are given explicit instructions how to perform the task during learning.

Results

Practice Session

Performance

For the Practice Session an exponential time course was expected for all performance measures indicating learning. Thus an exponential function of the type $f(x)=a+b*e^{-cx}$ was fitted to each subject's data across the 32 trials of learning. Figures 18- 20 display scatter plots of the individual performances for all trials and the plot for the mean fitted values. Mean goodness of fit for the Absolute Error was $R^2_{(adj.)}=.61$, for Period Modulation $R^2_{(adj.)}=.59$, and for Racket Acceleration$R^2_{(adj.)}=.51$. Thus these variables do indeed follow an exponential decay. Based on visual inspection of raw data of Covariation a linear fit of the type $f(x)=a+bx$ was applied to individual data but there was no significant fit to the data and mean R^2 (adjusted)<0. Participants apparently can exploit the task characteristic of Covariation from the beginning.

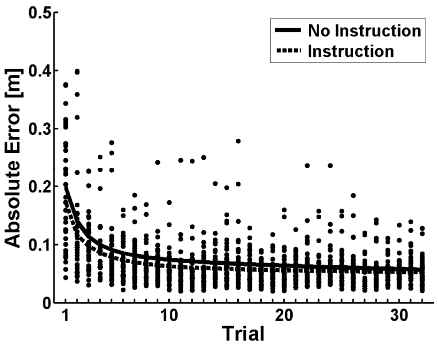

Figure 18. Overt performance (Absolute Error). Scatterplots of individual data across the 32 trials of the Practice Session and mean across fitted data.

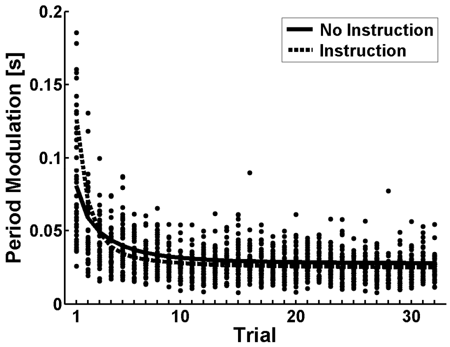

Figure 19. Covert performance (Period Modulation) Scatterplots of individual data across the 32 trials of the Practice Session and mean across fitted data.

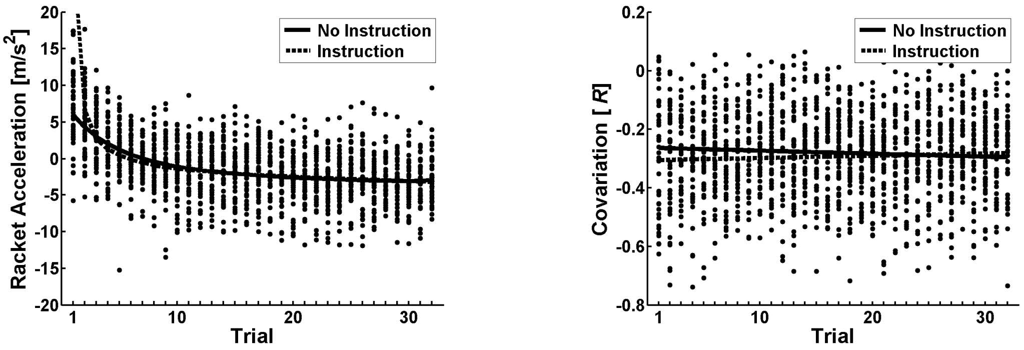

Figure 20. Task exploitation. Scatterplots of individual data across the 32 trials of the Practice Session and mean across fitted data (Acceleration at Impact (left) and Covariation (right). Note that for Covariation a linear fit was applied but no significant fit was found.

Although no differential learning effects between the two Instruction Groups were apparent from figures 18- 20, estimated (fitted) values for the last trial of the Practice Session (trial 32) for all measures were compared. No significant difference between Instruction Groups was found for any measure (Absolute Error: $F(1,36)=1.46$, $p>.05$, $f=0.20$; Period Modulation: $F(1,36)=2.48$, $p>.05$, $f=0.26$; Racket Acceleration: $F(1,36)=0.05$, $p>.05$, $f=0.0$; Covariation: $F(1,36)=0.28$, $p>.05$, $f=0.09$).

Manipulation Check (Practice Session)

In order to assess whether providing explicit technique-oriented instructions was successful in directing the focus of attention towards execution of the skill the errors in tone judgment were analyzed. Instead of using the number of false judgments the error rate was computed by dividing number of false decisions by the number of answered prompts, because in some instances answers had not been recorded. Then the mean error rates in the tone judgment Task were compared with a 2 (Groups) x 2 (Tasks: "pitch" vs "direction") ANOVA with repeated measures on the last factor. As can be seen in table 2 participants were generally more accurate in judging the tone pitch than in judging the direction of movement during tone occurrence ($F(1,37)=36.33$, $p<.05$, $f=0.99$). Yet there is no significant interaction between Task and Instruction Group ($F(1,37)=0.34$, $p>.05$, $f=0.10$).

To evaluate the reliability of the tone-judgment task, a split-half-reliability was calculated. For both tasks reliability is very low with $r_{tt}=.11$ for the "direction"-task and $r_{tt}=.34$ for the "pitch"-task. Also the statistical independence of the two tasks was evaluated: a negative correlation of $r=-.24$ ($p>.05$) was found.

Table 2. *Means and standard deviations of error rates in the tone judgment task. Lower error rate in "direction of movement" indicates focus of attention directed to movement (Gray, 2004).*

	Task	
Group:	direction of movement	tone pitch
No Instruction	0.45 ± 0.19	0.16 ± 0.14
Instruction	0.43 ± 0.18	0.19 ± 0.18

Evaluation of explicit knowledge

To evaluate the amount of explicit knowledge accrued, first the number of rules reported as answers to the two questions was analyzed. As can be seen in table 3, the Instruction Group reported more rules of advice (question 1) in general ($F(1,36)=4.44$, $p<.05$, $f=0.35$), and of these, there were more "old" rules (rules that directly referred to

Table 3. *Means and standard deviations of number of rules reported.*

	number of rules		
Group:	"advice" (question 1)	"old" (out of advice)	"action" (question 2)
No Instruction	1.35 ± 0.49	0.45 ± 0.60	1.30 ± 0.47
Instruction	1.89 ± 1.02	1.0 ± 1.28	1.44 ± 0.70

the above mentioned instructions – $F(1,36)=2.87$, $p<.05$, $f=0.29$). They did not report significantly more rules about what action leads to stable performance (question 2 - $F(1,36)=0.56$, $p>.05$, $f=0.12$).

The content of the rules of advice and action-rules were further evaluated separately by two independent raters. All rules were classified into one of the five categories shown in table 4. Initially the two raters did not agree in 24 cases (=31%) for rules of advice and in 18 cases (=26%) for rules of action. In a discussion, the deviating ratings were defined as errors and corrected (9/8) or were classified in a mutual decision (8/10), no decision could be reached in 7 and 9 cases, respectively. The No-Instruction group reported relatively fewer rules of advice that referred to the execution of the movement (body part, and range of motion) than the Instruction group. No such group differences can be seen for rules of action, where both groups primarily refer to body parts as being important for stable performance (see table 5).

Table 4. *Category system for the examination of explicit rules as answers to open questions*

#	Category	Prototypical answer
1	Body parts	"lower arm movement, not wrist"
2	Range and position	"having a consistent range of motion"
3	Pace and Rhythm	"a steady rhythmic up-and-down movement"
4	Focus	"focus on the point you're trying to hit, the red line"
5	General	"stay relaxed with one fluid motion"

Table 5. *Distribution of rules given by participants across the categories.*

	Rules referring to			
	advice		action	
	Instruction Groups		Instruction Groups	
category	No	With	No	With
1	0	10	12	15
2	2	6	6	4
3	9	10	8	9
4	6	8	1	1
5	9	6	1	3
Sum	26	40	28	32

Lastly it was analyzed how the amount of explicit knowledge (measured through number of reported rules) relates to explicit monitoring (measured by judgment error in the direction task). From the reinvestment hypothesis (cf. Master & Maxwell, 2004) this relation should be high: the more explicit knowledge the fewer direction- errors. Significantly negative correlations are found, although with both tasks (table 6).

Table 6. *Correlation coefficients between number of rules reported and % errors in the tone judgment tasks.*

	judgment error	
Number of rules reported by…	direction	pitch
No-Stress Groups	.03	.13
High-Stress Groups	-.53*	-.51*

Note: * significant at α<.05

Performance Session

In order to analyze performance under pressure the performance in the Baseline and Performance Test was compared with a 2 (Instruction Groups) x 2 (Stress Groups) x 2 (Tests) ANOVA with repeated measurement on the last factor.

Manipulation Checks

As Table 7 indicates, an increased level of anxiety in the High Stress Groups was found before the Performance Test, however this interaction was not statistically significant (Test x Stress group: $F(1,35)=2.57, p>.05, f=0.27$). Only a significant main effect of differences between Stress Groups ($F(1,35)=9.50, p<.05, f=0.52$) was found. Secondly, it was analyzed, whether participants in the High Stress Groups were convinced that they had entered a true competition: 9 participants were completely convinced, 6 appeared to have some doubts, 3 were quite doubtful and 2 participants did not believe it at all. Although the pressure manipulation may not have been successful with the latter 2 their data was not excluded from analysis because they showed increases in the state-anxiety level by 8 and 18 points.

The second part of the manipulation check was with respect to the focus of attention and therefore error rates in the tone judgment task were compared. A 2 (Instruction Groups) x 2 (Stress Groups) x 2 (Tests) x 2 (Tasks) ANOVA with repeated measurements on the latter 2 factors was computed. Again, participants committed

Table 7. *Group size and Means and standard deviations of STAI-state scores.*

			Test	
Group		*n*	Baseline	Performance
No-Instruction	No Stress	10	28.40 ± 3.78	28.70 ± 6.06
	High Stress	11	34.64 ± 9.72	37.46 ± 9.83
Instruction	No Stress	9	27.78 ± 5.78	25.78 ± 5.26
	High Stress	9	31.22 ± 4.79	33.29 ± 8.26

fewer errors in judging the pitch of the tone than in judging direction of movement during tone occurrence (Task: $F(1,35)=70.86$, $p<.05$, $f=1.42$). The specific expectation was that fewer errors would occur in judging direction of movement for the Stress Group with Instruction in the Performance Test. However, the 4-way interaction (Group x Instruction x Test x Task) was not significant ($F(1,35)=0.80$, $p>.05$, $f=0.15$). From figure 21 it appears that within the Stress Groups, the Instruction Group makes fewer direction-errors and more pitch errors on the Performance Test than in the Baseline Test, while the No-Instruction Group behaves exactly contrary. A 2 (Instruction Groups) x 2 (Tests) x 2 (Tasks) ANOVA with repeated measures on the latter 2 factors was computed for the Stress Groups to test this difference. However, the 3 way interaction was not significant ($F(1,18)=1.41$, $p>.05$, $f=0.28$).

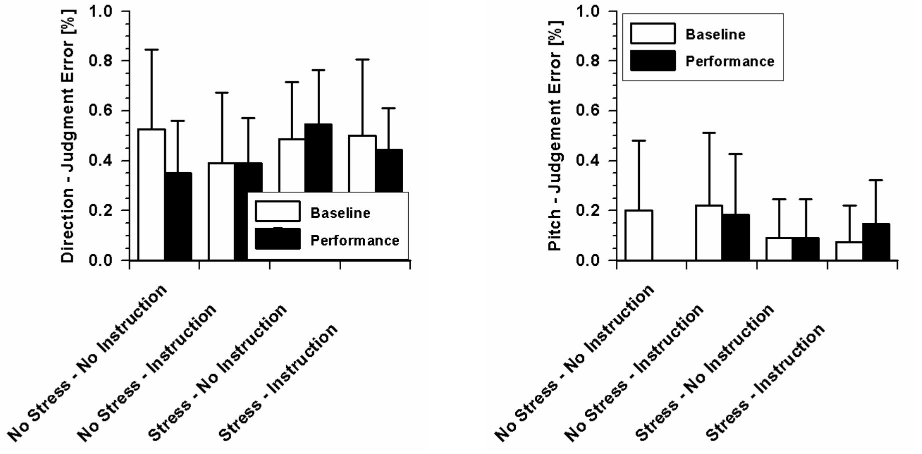

Figure 21. Tone Judgment Task: % Errors in judging direction of travel of racket (left) and pitch of the tone presented (right). The No-Stress – No Instruction Group made no error in pitch-judgments.

Performance measures

Absolute Error from the target height in the Performance Test was significantly more accurate for the Stress Groups than for the No-Stress Groups (Group x Test: *F*(1,35)=8.51, *p*<.05, *f*=0.49) but no interaction was found with Instruction (Group x Instruction x Test: *F*(1,34)=0.85, *p*>.05, *f*=0.16). Figure 22 displays mean Absolute Error from target height for the Performance Session. There was also no significant difference between the four groups in the Baseline Test (*F*(3,35)=0.60, *p*>.05, *f*=0.23). Looking only at the two Stress Groups, there is only a significant main effect (Test: *F*(1,18)=9.01, *p*<.05, *f*=0.71) but no interaction between Instruction Groups and Test (*F*(1,18)=0.11, *p*>.05, *f*=0.08).

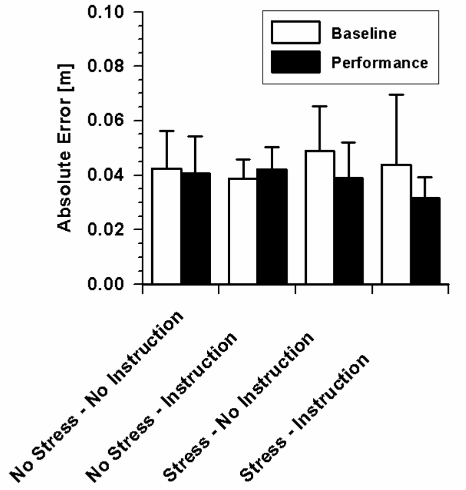

Figure 22. Overt performance in the Performance Session (Means and standard deviations of Absolute Error from target height).

It was further evaluated, whether it would be worth analyzing only participants that performed worse under pressure. But only 2 participants of the Stress Groups yet 10 of the No-Stress Groups showed performance decrement. Also the correlations between anxiety scores and Absolute Errors were examined. To this end, first difference scores between Baseline Test and Performance Test were computed. For the No-Stress Groups a non-significant positive correlation of *r*=.34 was found, for the High-Stress Groups a non-significant negative correlation of *r*=-.16. The more increase in anxiety score, the more participants could reduce the Absolute Error.

Similar to the Absolute Error there was significantly lower Period Modulation in the Performance Test for the Stress Groups (Group x Test: *F*(1,35)=4.41, *p*<.05, *f*=0.36) but again no interaction with Instruction was found (Group x Instruction x Test: *F*(1,35)=0.08, *p*>.05, *f*=0.0). Looking only at the two Stress Groups, there is a significant main effect (Test: *F*(1,18)=10.94, *p*<.05, *f*=0.78) and also a significant interaction between Instruction Groups and Test (*F*(1,18)=7.17, *p*<.05, *f*=0.63). Participants in the No Instruction Stress Group were able to reduce Period Modulation in the Performance Test, while the Instruction Stress Group was not (see figure 23).

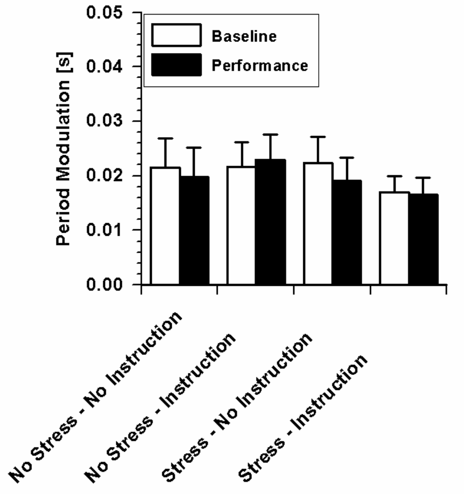

Figure 23. Covert performance in the Performance Session: Mean and standard deviation of Period Modulation.

However no similar effects was found for acceleration (AC, see figure 24): The 2-way interaction between Group and Test was not significant (*F*(1,35)=0.43, *p*>.05, *f*=0.11), as well as the 3-way interaction Group x Instruction x Test (*F*(1,35)=3.86, *p*>.05, *f*=0.33). Looking only at the two Stress Groups, there was no significant main effect of Test (*F*(1,18)=.18, *p*>.05, *f*=0.10) and no interaction between Instruction Groups and Test (*F*(1,18)=0.23, *p*>.05, *f*=0.11).

For Covariation a tendency for higher Covariation of the Stress-Group in the Performance Test was found (see figure 24), which did not reach statistical significance (Group x Test: *F*(1,35)=3.26, *p*>.05, *f*=0.30). There was also no 3-way interaction Group x Instruction x Test (*F*(1,35)=0.12, *p*>.05, *f*=0.05). Looking only at the two Stress Groups, there was no significant main effect of Test (*F*(1,18)=2.32, *p*>.05, *f*=0.36) and no interaction between Instruction Groups and Test (*F*(1,18)=0.71, *p*>.05, *f*=0.20).

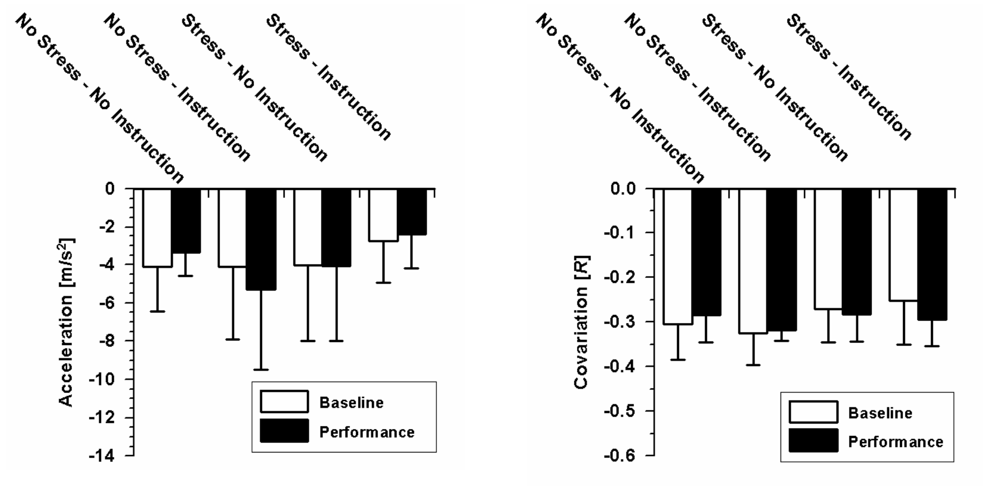

Figure 24. Task exploitation in the Performance Session (Means and standard deviations of Acceleration at impact (left) and Covariation of impact parameters (right).

Discussion

Results in experiment 2 are in line with findings from experiment 1: There was no choking under pressure. Participants in the fake competition were able to increase their overt performance, i.e. reduce their absolute error, whereas participants in the No-Stress Groups were not. This was irrespective of any instructions that participants had received during learning. The same finding extends at least partially to covert performance, with an increased consistency in the cycle period under stress in the group that had not received explicit instructions. Exploitation of the dynamical stability through negative acceleration of the racket at impact was virtually unaffected by the stress manipulation. For the covariation of the parameters at impact that determine ball height there was a tendency for increased exploitation of that task characteristic under pressure. In addition to finding support for results from experiment 1, experiment 2 was designed to test whether participants did not choke because they did not use an explicit monitoring strategy. To this aim first of all half of the participants in experiment 2 were provided with instructions on how to perform the task. Masters (1992, Liao & Master, 2002) found explicit monitoring (and performance failure) under stress only in participants who had received explicit instructions during learning, but not in participants who had learned the task implicitly. But results in Experiment 2 show that explicit instructions had no effect on learning the task, and more importantly, they also had no effect on the performance under pressure. Secondly, explicit knowledge of participants was evaluated after learning the task. Participants that had received instructions did indeed report more rules and these rules were also distinctively referring to the execution of the movement. When asked what action or behavior specifically leads to stable performance, both groups mainly refer to body parts involved (about 50 % of the answers) and less to the use of a steady pace or rhythm (about 30% of answers). Still, obviously participants are able to observe that the period of the racket (i.e. the pace) plays a crucial role for stable performance. Thirdly, an attempt was made to measure directly whether participants are focusing on the execution of the skill ("explicit monitoring"). To this aim a tone-judgment task developed by Gray (2004) was used. Performers were asked to either judge whether a presented tone was of a certain frequency or "pitch" or whether the tone occurred during an up or down motion of the arm ("direction"). Fewer errors in the "direction" judgment would indicate a focus of attention directed towards the movement and its execution, fewer errors in the "pitch" judgment would indicate use of an external focus of attention (Gray, 2004). No differences in the judgments were found between instructions groups and more importantly, participants in the pressure situation did *not* make fewer errors in the "direction" judgment. Taking these results together it appears as participants in the ball bouncing task are not "explicitly monitoring" the task under pressure despite the fact that explicit knowledge was accrued.

Two caveats have to be added before the further discussion: First, in this experiment and in contrast to experiment 1, the stress manipulation appears to have not been very successful because no significant increase in state anxiety was found for the Stress Groups. Second, the tone judgment task has to be interpreted with caution because its reliability is low.

General Discussion of Study 1

The cardinal question of this dissertation is what sensorimotor mechanism could be behind the phenomenon of choking under pressure. In order to answer this question the "import" of the nodalpoint hypothesis of motor control (Hossner & Ehrlenspiel, 2006) was proposed into the research program concerned with the phenomenon. This hypothesis suggests a sensorimotor mechanism behind "explicit monitoring" or an "internal focus of attention" – which have been argued to underlie the phenomenon of choking under pressure (e.g. Beilock & Carr, 2001). The nodalpoint hypothesis assumes a sequence of nodalpoints as the control structure of movements and it makes two key predictions: Focusing or explicitly monitoring such a nodalpoint results in (1) reduced exploitation of task space, and more specifically (2) at that nodalpoint. The aim of Study 1 was to examine the first of the key predictions. To this aim participants learned and performed the simple motor skill of bouncing a ball. For this task stability analyses have shown, that dynamical stability occurs, when the ball is impacted with the racket with a negative upward acceleration (Sternad, Duarte, Katsumata & Schaal, 2001). Human actors are able to exploit this characteristic of the task after learning. In this study, performance in the task was evaluated on three levels of analysis: overt performance, the outcome measured in extrinsic space (absolute error), covert performance, the execution of the movement measured in intrinsic space (modulation of the racket period), and task exploitation, the utilization of the task space measured in both intrinsic as well as extrinsic task space (dynamical stability and covariation of impact parameters). It was hypothesized that (1) participants in a pressure situation should show decrement of performance on an overt and covert level (2) due to reduced exploitation of task space under pressure. Surprisingly, in this study no choking under pressure was found. Participants who entered a fake competition performed better in this pressure situation compared to an individual baseline performance and to participants who continued the experiment without changes to the situation. Clearly, with this result the cardinal question about the mechanism behind choking can not be answered – because there was no choking after all!

Results of Experiment 1 were already discussed with reference to the formalized development of empirical hypothesis put forward by Herrmann (1976) and which was used to derive hypotheses from theoretical core assumption in this study, as well. The general discussion of Study 1 can also be organized along this frame. Also, following action-theoretic concepts of behavior (Nitsch, 2004), this discussion will analyze three aspects: the situation, the person and the task.

Concerning the "basic level" of experimental and methodological issues, it has to be asked with respect to the situation whether the experimental manipulations were effective. Possibly, the induced "pressure" was not enough to elicit choking because participants might not have experienced something being at stake. In this vein the fake competition may not have induced enough "pressure" to raise anxiety and therefore did not lead to explicit monitoring. Data from experiment 1 and 2 is somewhat inconclusive because significant increases in levels of anxiety – indicating perceived pressure – are only reported in experiment 1 but not in experiment 2. Although it thus seems that the stress manipulation was not very effective it must be noted that other studies have used the same manipulation and have found choking. Also, certainly no evidence was found for explicit monitoring in the stress situation – whether this is owed to the ineffective pressure situation or not. But even giving explicit instructions in Experiment 2 obviously did not lead to the adoption of an internal focus of attention (or „explicit monitoring") throughout the experiment. Participants in the Instruction Groups after at least initially focusing on the movement tended to increasingly focus away from the movement execution, even in the pressure situation. Giving instructions, however, did lead to the accrual of explicit knowledge. Still, in contrast to previous studies using the same manipulations and manipulation checks creating pressure in this experiment was not very successful, and evidence for evoking explicit monitoring is missing.

Considering the person, many studies have found interindividual factors to influence the pressure-performance relationship (e.g. Beckmann & Strang, 1992; overview: Baumeister & Showers, 1984). It is feasible to believe, however, that these interindividual differences were equally distributed over the experimental groups. Also, in Experiment 2 balancing of the experimental groups with respect to performance in the Baseline Test was more successful than in experiment 1. One possible factor doubtlessly affecting the pressure-performance relationship could be expertise. Some studies suggest that increased explicit monitoring is helpful for novices learning a new task (Beilock, Carr, MacMahon & Starkes, 2002; Perkins-Ceccato, Passmore & Lee, 2003) whereas it impairs performance in experts. If participants in this study were still learning the ball bouncing task (i.e. they were "novices") than this may explain their performance enhancement in the pressure situation. A number of observations speak against this explanation: Participants' learning curve of overt performance follows an exponential function leading to a mean absolute error of smaller than 10 cm at the end of the Practice Phase and of about 5cm in the Performance Phase. Comparable learning is observed in covert performance, where the Cycle Period is varying around 50ms in the Performance Phase. Although it can not be ruled out completely, learning does not seem to continue after the Practice Session.

Concerning the validity of the secondary assumptions the discussion leads to a scrutinizing of the task. It has for long been a matter of heated debate what aspects of a task may lead to choking or facilitation under pressure (overviews for example in Bond & Titus, 1983; Strauss, 2002). Distinctive features have been thought to be complexity, type of performance (quantitative vs. qualitative) or respective motor abilities (coordination, physical fitness). Although the category of "complexity" is hard to define (e.g. Wulf & Shea, 2002), the task of ball bouncing resembles a rather simple skill. It is fairly easily learned and in the experimental set-up used it is performed only in one dimension (up-and-down movement of arm). Although there is some demand for eye-hand coordination it is undeniably reduced when dynamical stability is exploited. In line with the results of experiment 1 and 2, some evidence exists that in these types of tasks performance is actually enhanced in pressure situations detrimental (Bond & Titus, 1983; Strauss, 2002). It is unclear from these studies, also, why this is the case. It may very well be that in easy tasks, actors despite feeling under pressure are very self-confident and subsequently do not choke (on the moderating role of self-confidence see e.g. Hardy, Woodman & Carrington, 2004). This may also be the case in the two ball bouncing experiments. On the other hand, (overt) performance is measured rather qualitatively because accuracy is assessed and not speed or number of errors, and for these types of tasks, pressure seems detrimental (Bond & Titus, 1983; Strauss, 2002)! A further critical feature of the task examined could be its continuous nature. The tasks in previous studies focusing directly on choking under pressure have almost exclusively used discrete tasks such as a golf putt (e.g. Master, 1992; Hardy, Mullen, and Jones, 1996, Beilock & Carr, 2001). In such tasks a considerable amount of time is spent with preparation for and planning of the movement. If performers start out with planning a task step-by-step, then they may be more likely to also execute or control it in a step-by-step manner. Additionally, a continuous task with its longer duration may leave room for action- control strategies to overcome pressure and explicit monitoring. Thus, either as a consequence of the lack of pressure or because of the nature of the task, no explicit monitoring may emerge.

At this point it has to be acknowledged that because of doubtful experimental validity and also a questionable validity of the secondary assumption, i.e. the general hypotheses for Study 1, the core assumptions need to remain unchallenged. Assumptions about the problem of choking – pressure leads to explicit monitoring which in turn leads to poor performance – as well as about the nodalpoint hypothesis – attention focused on nodalpoints leads to reduced exploitation of task space at the nodalpoints in focus – were apparently not tested. Explicit monitoring was not elicited – it can be argued that this is due to the lack of the experience of pressure but it looks promising further inspect the nature of the task. In so far we can take the results of Study 1 as support for the notion, that the phenomenon of choking is a result of explicit monitoring of the task.

Study 2

Tracking under Pressure –
Two Become One but does One Become Two?

Study 2

The aim of this dissertation-project is to investigate possible mechanisms that could be behind the phenomenon of “Choking under Pressure”. To this end it was assumed that this phenomenon constitutes a “potential model” (Westermann, 2001) of the nodalpoint hypothesis of motor control (Hossner & Ehrlenspiel, 2006). The hypothesis assumes a sequence of “nodalpoints” as the control structure of movements, which are basically effects of elementary behavioral acts. Over the course of learning a motor skill, these effects or nodalpoints are chained to form chunks of effects. Two consequences arise from this process: First, it is not necessary to focus attention on every single act and the focus can be shifted from intermediate effects to the final effects of the movement usually occurring in the distal environment. Secondly, within the chain of effects points of more or less “prominence” evolve (cf. Hoffmann, 1993). These boundaries of chunks arise at points of relative uncertainty about continuation. If there is a relative unpredictability of the next effect attention needs to be directed to whether the expected (or “anticipated”) effect occurs. In contrast to the “external focus of attention” which is directed to distal effects in the environment, an “internal focus” can thus be directed towards these intermediate effects within the sequence of nodalpoints. In this case the nodalpoints are thought to be “controlled” (Hossner & Ehrlenspiel, 2006). Again, there are two key features of the nodalpoint hypothesis that are (a) its predictions about reduced exploitation of task space formulated on an operational level and (b) its time-referenced character, i.e. that these changes are expected to occur at certain (nodal-)points in time. The aim of Study 2 was to examine the second of these two key features. Although all nodalpoints may serve as anchors of attention, some prominent nodalpoints within a sequence exist where there is relatively more uncertainty about the next effect. From these assumptions it is hypothesized that under pressure actors focus their attention towards prominent nodalpoints of the movement. At these nodalpoints in focus they should show reduced task exploitation.

In Study 2 the predictability of effects – that is the prominence of nodalpoints – was manipulated by using a classic strategy for teaching motor skills: part-whole learning. When students, for example, learn the high-jump one can often see them first learn the approach to the bar which just ends with a small hop. Then they practice to jump over the bar, often starting off two feet. Finally the two parts are concatenated and students approach the bar and jump over it. Similar learning strategies have been investigated in pianists (Williamon, Valentine & Valentine, 2002; see also Park, Wilde & Shea, 2004). It is the basic underlying general assumption of Study 2 that at the point where the two parts are concatenated a prominent "nodal point" exists. At this point a local uncertainty about the progression of the movement exists. Over the course of learning the parts combined the prominence of this nodal point should vanish (see figure 2 in the Introduction). However, under pressure, the nodal point should re-emerge and serve as an anchor for attention. It therefore may be hypothesized that if two sequences of nodalpoints are first learned separately and are later concatenated to form a single sequence, performance under pressure should lead to the control of the prominent nodalpoint at the concatenation.

The paradigmatic task to investigate sequence learning has become the serial reaction-time (SRT) task. In this task stimuli are successively presented to which participants have to respond as quickly as possible, usually by pressing a corresponding key. In structured stimulus sequences the reaction time decreases faster and often to a lower level than in random structures. This is seen as evidence of sequence learning. "Structure“ in the stimulus material has mainly been generated through a statistical structure, either by fixed sequences (e.g. Nissen & Bullemer, 1987) or finite-state grammars (e.g. Reber, 1967). But also an underlying temporal (Stadler, 1993) or spatial structure (Koch & Hoffmann, 2000) in the task has been shown to result in sequence learning. All of these studies have used only a simple and discrete movement to investigate sequence learning, and a transfer to complex motor skills has only rarely been attempted. There certainly is problem, as "principles derived from the study of simple skills do not generalize to complex skill[s]" (Wulf & Shea, 2002, p.185) – although a "necessarily" may be inserted behind the "not". Hossner (2004) has been one of the first to apply the SRT-task to more complex movements, using both fixed sequences as well as finite-state-grammars. However, a complex task that has been used extensively in research on mechanism in motor control can be regarded as representing a serial reaction task (Rosenbaum, Carlson & Gilmore, 2001): the visuomotor tracking task. In this task participants have to follow a target displayed on a monitor using some manipulator like a joy-stick or computer mouse. Usually the target follows some sinusoidal waveform defined by (series of) functions. Although this function is of course continuous the turning points, i.e. the local maxima and minima, represent "events". These events give the task a temporal and spatial structure. Also, the analyses of eye-movements have rendered the notion that control of tracking may be of discrete nature (Roerdink, Peper & Beek, 2005). This task is certainly complex as different processes of continuous and parallel nature are involved including eye-hand coordination and timing. Many studies have investigated control strategies for this task (e.g. Hill & Raab, 2005; Schorer & Raab, 2006; Weir, Stein & Miall, 1989). They have shown that visual feedback and visual feed-forward control is involved as well as more stable internal representations of the target. Under visual feedback errors are corrected online by using (and reducing) the distance between a target and the controlled object position. Under visual feed-forward, short term predictions about the future position (and change in position) of the target are used to make preventive adjustments. Internal representations are rather long-term predictions of the path of the target object and allow long term movement planning. Miall and Wolpert (1996) have also argued for implementational models of these control strategies. In the studies, the temporal lag between target object and pursuit object has been used as an indicator of these strategies, with a positive lag indicative of feedback control (e.g. Weir, Stein & Miall, 1989). However, this lag has so far only been investigated with respect to the entire task and not just the events of the turning points. If these events play a role in providing a control structure to the task, than they should be investigated in more detail.

From a nodalpoint hypothesis perspective these events or turning points represent nodalpoints as they are clearly distinguishable effects of behavioral acts. The transition from one turning point to the next can be seen as a SRE-triplet and if there is a structure behind the turning points than these triplets should be chained to form a sequence. Concurrently a shift from feedback to feed-forward control should take place, because the effects at each turning point (change of direction) are reliably predicted. The visuomotor tracking task is therefore used to test whether the nodalpoint hypothesis can be imported to provide for a sensorimotor mechanism behind the phenomenon of choking under pressure. Two sequences of turning points will be learned first separately and then concatenated. Under pressure it can be expected that attention is directed to the prominent turning point at concatenation (it is explicitly monitored), leading to feedback control and reduced task exploitation at that nodalpoint.

General Hypothesis for Study 2

Based on the assumptions that (a) psychological pressure leads to increased self-monitoring, i.e. a focus of attention directed to the movement or task, and that (b) this self-monitoring leads to nodalpoint control the general hypothesis for Study 2 was phrased as:

> S_2: A fake competition with financial incentives leads to "pressure" and consequently to decrements in overt performance (accuracy from target) in a continuous visuomotor tracking task as a result of reduced covert performance (movement timing) and task exploitation (reduced covariation between intervals) at a prominent nodalpoint due to an explicit monitoring of the task.

Experiment 3

In addition to exploring control-strategies such as feed-forward or feedback processes the visuomotor pursuit tracking paradigm has also been used to investigate implicit learning (e.g. Magill, 1998; Wulf & Schmidt, 1997; Pew, 1974). In these studies the target follows a function that is in fact a sequence of three functions of equal length. In this sequence the middle function (or segment) remains the same throughout the experiment, whereas random parameters are introduced in the two outer sequences (or segments) to produce random functions across trials. It has repeatedly been shown that learners are able not only to follow the target more accurately in general but especially in the constant middle segment. However, when being asked whether they have noticed any patterns in the task usually participants do not report any pattern or regularity. This approach was also used to "teach" the two sequences in experiment 3, first separately and then jointly. Yet some critical issues in the tracking paradigm as applied previously were altered. First of all, rather than using functions to produce the target sequence splines across pre-defined turning points were used. This way it could be experimentally secured that random segments and constant segments were indeed equally difficult – a point that has not adequately been addressed in previous studies by using an obscure "difficulty index" (Schorer & Raab, 2006; Wulf & Schmidt, 1997). This will be explained in detail in the methods section. A second critical issue concerns the manipulandum: Previous studies used, as mentioned, either a computer mouse or a joystick to control a pursuit cross, for example, that follows the target. Besides potential mechanical perturbations when using a computer mouse the main question is how the movement of the arm is related to the movement of the pursuit cross. The studies give no information on that relation, i.e. the “gain” of the “real” movement to the movement of the “virtual” pursuit cross. Therefore in this study a digitizing tablet was used where participants hold a pen in their hand which can be moved with minimum friction on the tablet. The gain was determined as 1, i.e. the movement of the tip of this pen corresponded to the movement of a virtual cross on the computer screen.

Methods

Participants

32 participants were recruited for this study. The 19 male and 13 female participants (age 16-32) were mainly undergraduate students in sport science and psychology. Participants received extra credits in an undergraduate class as compensation for participation. Additionally, all participants were given the €5 offered in the competition (see below). The participants were informed about the experimental procedure and signed a consent form. One participant did not return for the Performance Session on day 2, thus data of 31 participants could be analyzed. Three of these participants did not show accurate enough performance in the warm-up blocks in the Performance Session (performance more than 2 SD from sample mean), and their data was also discarded, resulting in a final sample size of *N*=28.

Task and apparatus

A tracking task similar to the one by Magill (1998) was used to test hypotheses. Participants were seated approximately 50 cm in front of a computer monitor (17" screen, resolution 1024 x 746 dpi) with a black screen. On the screen a red target cross (lines: 25 * 3 pixel) was displayed which once a trial was started moved from the left side of the monitor to the right side. The participants were instructed to closely follow the target cross with a white pursuit cross (lines: 20 * 2 pixel) which they could control using a pen on a digitizing tablet (AIPTEK Hyperpen 2000). The red target cross followed an invisible curve, which was constructed by defining turning points rather than functions, which were used by Magill (1998) or in the original work by Pew (1974). Splines were fitted to the turning points to produce a smooth curve. This curve consisted of three segments (a left, middle and right segment) of equal length, each segment consisting of 6 turning points spaced equally on the horizontal axis. As was mentioned above, in the Pew and Magill paradigm, different functions were used for the three segments. And whereas in the middle segment the same function was used in all trials to produce a constant segment, the left and right segment used randomly produced functions. At least two problems are associated with the use of functions, however: First, the (vertical) location of the constant curve may vary to some degree and second, it is difficult to prove that random and constant curves are equally difficult. Therefore, in this study a set of 30 sections each consisting of 6 turning points was defined (= length of a segment). Three of these sections were then concatenated to produce the entire curve. For random segments a randomly chosen section from the set of sections was used, constant segments always used the same section (varying inter-individually). The set of 30 sections was constructed as follows (following a rationale developed by Hossner, 2006): Vertically, the turning points could take 1 of 7 potential vertical positions, with the (vertical) center of the screen as a “0”-position. The other 6 potential positions were spaced around this center in single units in multiples of 110 pixel (see figure 25). Each section produced 3 up- and down movements, respectively, which could be either 1, 2 or 3 vertical units in length. Furthermore, each movement length was produced only once and every “up”-movement was followed by a “down”-movement, thus the section started and ended at the same vertical position. With these boundary-constraints a set of 3(up) x 3(down) x 2(up) x 2(down) x 1(up) x 1(down) =36 sections was produced. Six “easy” sections where an up-movement was followed by the same down-movement were deleted resulting in the final set of 30 sections from which segments were chosen. The entire curve then consisted of a start segment of a start-position and 2 turning points, three segments with one of the 30 sections (=18 turning points) and an end segment of 1 turning point and the end-position, totaling 21 turning points. Start- and end-position were at the “0” vertical position, in an attempt to slightly obscure the regularity of the curve, the position of the first and last turning points were randomly chosen from the +1 or +2 position on every trial. Finally, in order to be able to select any section in any of the three segments, the second turning point was always at the -1 position (see figure 25).

The target cross moved across a distance of 990 pixel on the x-axis with a constant velocity in the x-direction for a duration of 19s. The display of target and pursuit cross position was sampled at a refresh rate of 60Hz. Data of target and pursuit cross position was recorded at a frequency of approximately 25Hz (470 data samples).

In this study, sections were presented in either single or combined presentation. In the single presentation during the Practice Session the constant section was presented

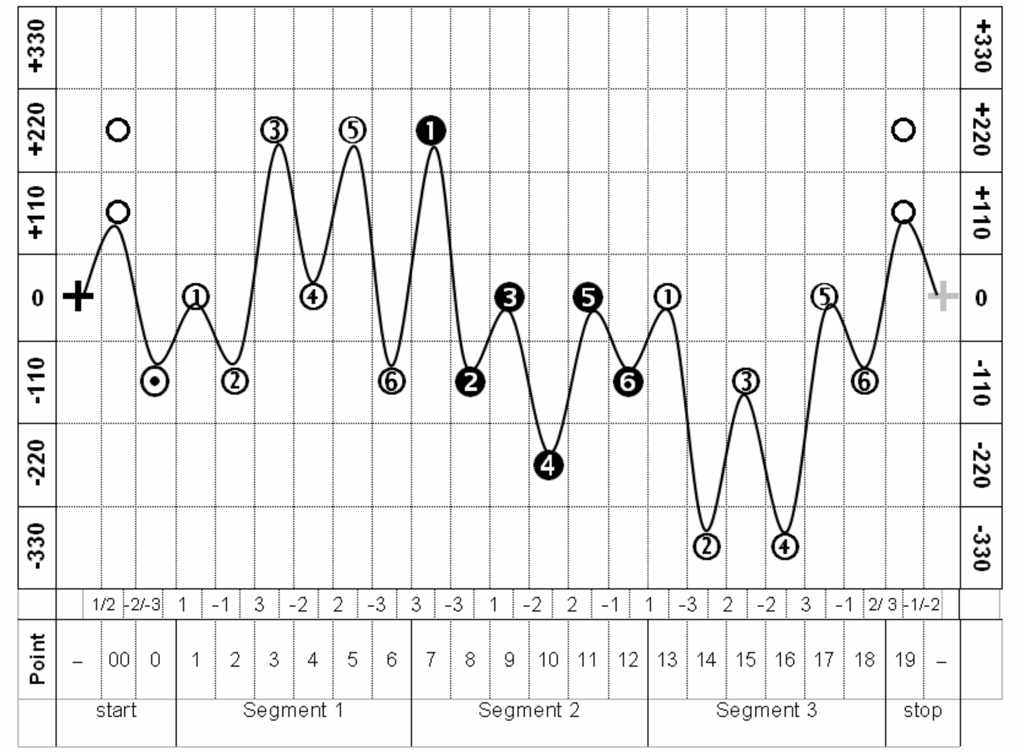

Figure 25. Description of the tracking curve. Three segments were defined by 6 points (a "section"). A spline was fitted to the points to produce a continuous curve. The target cross followed this curve, which was invisible. The movement of the target started from and stopped at the 0-position, for the start- and stop segments either of two points were chosen.

in the middle segment, and in segments 1 and 3 sections randomly chosen sections from the set of 30 sections described above were presented. Participants first learned two sections (section A and section B) separately in single presentations. This presentation can be denoted as RAR or RBR with R for "random" and A/B for a constant section. Constant sections were chosen randomly between participants from the set of sections. In the combined presentation previously single-presented sections were combined to a section across two segments of the curve. Another randomly chosen segment either preceded or followed the combined sections (i.e. RAB or ABR). This order was again permuted across participants but constant within participants.

Dependent variables

As in Study 1, it was again assumed that task performance could be described on three levels: overt performance, covert performance and task exploitation. Overt performance in the tracking task is measured by the root mean square error (RMS-Error), which measures the average deviation of the pursuit cross to the target cross over the entire curve. The general hypothesis underlying study 2 was that performance changes under psychological stress should occur at the prominent nodal point where the two sections are concatenated. Therefore performance at this turning point (i.e. nodal point) was analyzed in more detail and compared with all other turning points. Overt performance at a turning point was measured by the 2-dimensional Absolute Error (Hancock, Butler & Fishman, 1995) of pursuit- turning points from target-turning points within a block of trials. Covert performance at a turning point was measured by Latency of turning. Latency was measured by the temporal difference between pursuit- turning points and target-turning points, with positive values indicating that the pursuit cross was following the target cross. Increased latency should indicate increased use of visual feedback: If actors rely on the visual signal of the target cross changing directions rather then on their own timing, movement control is under feedback control rather then feed-forward control. Finally, task exploitation at a turning point was measured by the temporal co-variation at a turning point within a block of trials. If task exploitation occurs than fluctuations in the duration of the interval before a turning point should be compensated for by the duration of the interval following the turning point. To compute covariation the empirical variance is compared with a covariation-free potential variance (Müller & Sternad, 2003). First the duration of the interval between two successive turning points was assessed. Then the (empirical) duration of two successive intervals was computed. To calculate empirical variance within a block of trials, for every turning point the variance of the duration of these empirical intervals around a turning point was computed. To calculate potential variance within a block of trials, in a complete permutation the potential duration of two successive intervals was computed by combining all empirical realizations of the interval before a turning point with all empirical realizations of the interval after that turning point. The variance of these potential durations yields the potential variance. Covariation is then given by $(\text{Variance}_{(\text{empirical})}/\text{Variance}_{(\text{potential})})-1$ (Müller & Sternad, 2003).

For the analysis of these performance measures at the turning points, only the performance at turning points within the two constant sections was analyzed. Furthermore, of the turning points, only the performance at the first and the last turning point of a section was of interest. Therefore intermediate turning points 2-5 within a section were collapsed to intermediate 1 and intermediate 2 turning points (see figure 26).

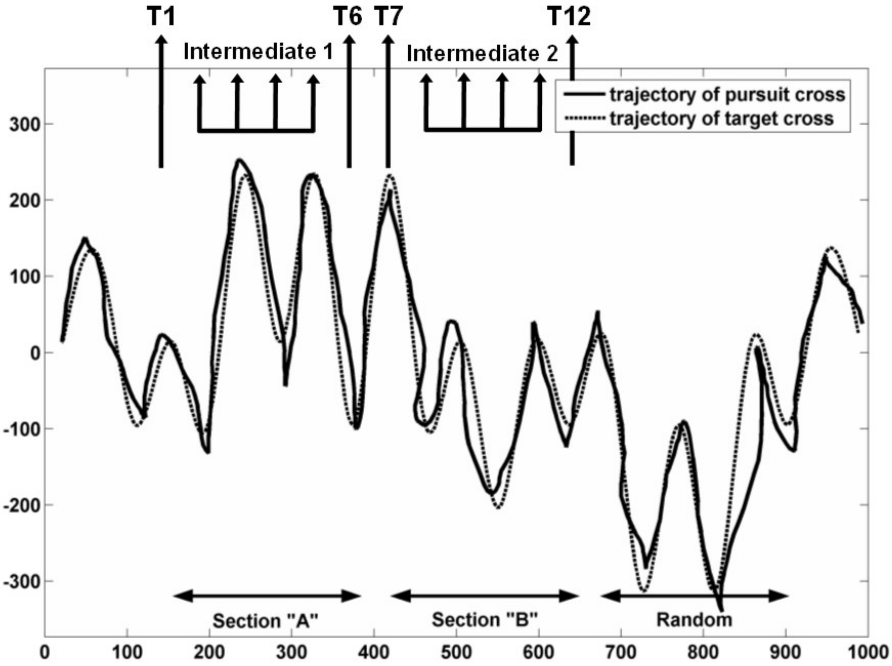

Figure 26. Exemplary data from one trial of combined presentation. For analysis, only turning points in the constant segments (sections A & B) were used. Further, the intermediate turning points 2-5 and 8-11 were collapsed and each compared to the first and also turning point of each section

Procedure and experimental conditions

The experiment consisted of two sessions performed on two consecutive days, a Practice Session and a Performance Session. After the participants were positioned in front of the computer monitor they were given details about the task, specifically they were asked to constantly and accurately follow the target cross with the pursuit cross. In the Practice Session, participants completed 8 blocks of 15 trials. Each trial lasted 19 s. Immediately after trials a text appeared on the screen for 2 s which displayed a score that gave the RMS-Error (in pixel) across the trial. Participants were informed that this number represented the average deviation from the target cross and that over practice, this number should get smaller. In between the blocks there was a 3 to 5 minute break in which participants were given the chance to take a rest. Over the first 6 blocks, each single section was presented in three blocks (=45 trials) with only either one of the two single sections A or B presented in the middle segment 2. In the first two blocks in segments 1 and 3 also the single section was presented (leading to an AAA/BBB presentation), in blocks 3-6 randomly selected sections were presented in segments 1 and 3 (leading to RAR/RBR presentations). In blocks 7-8 the combined sections were presented, leading to an ABR or RAB presentation (see table 8). The order of presentation in blocks 1-2, blocks 3-6 and the combination RAB/ABR were permuted interindividually. In the Performance Session, participants first were asked to fill out the German version of the State-Trait-Anxiety Inventory (STAI, Spielberger, Gorsuch & Lushene, 1970; German: Laux, Glanzmann, Schaffner & Spielberger, 1981). The Performance Session consisted of a warm-up block of 20 trials and 4 blocks of again 15 trials each. In the warm-up block first single sections were presented for 5 trials each (RAR/RBR) and were combined for the last ten trials (ABR/RAB). Also performance feedback (RMS-Error) was given after every trial. Then four performance blocks followed: In an ABBA-experimental design, blocks 1 and 4 were designed as "No-Pressure" performance blocks in which participants were told to „show, how much you learned yesterday!" and asked to accurately follow the target cross. Blocks 2 and 3 constituted the "High-Pressure" performance blocks. In experiment 3 a real competition was used to induce psychological pressure. While participants during the Practice and the No- Pressure blocks performed the tasks in a small booth by themselves, during the High-Pressure blocks one side of the booth was removed so that participants were sitting next to each other (distance: ca. 2m). This

Table 8. *Overview over succession of blocks and presentations of sections*

		Block	# of trials	Presentation
Practice Session		1	15	AAA / BBB
		2	15	BBB / AAA
		3	15	RAR / RBR
		4	15	RAR / RBR
		5	15	RAR / RBR
		6	15	RAR / RBR
		7	15	ABR / RAB
		8	15	ABR / RAB
Performance Session	Warm-up	9	20	5x RAR, RBR, 10x ARB/RAB
	No-Pressure	10	15	ABR / RAB
	High-Pressure	11	15	ABR / RAB
	High-Pressure	12	15	ABR / RAB
	No-Pressure	13	15	ABR / RAB

manipulation of psychological pressure was chosen in order to create a more realistic situation very closely copying competitive situations in sports. To assess the level of anxiety, participants filled out STAI (Laux et al, 1981) again during the break between the two High-Pressure blocks.

Data analysis

The root mean square error (RMS-Error) of the pursuit to the target cross was computed based on raw position data across all three segments and excluding the start- and stop- segment. For further analyses the raw data was first resampled to an exact duration of 19s and an exact sampling frequency of 25 Hz via spline-interpolation. Position data was then filtered with a digital Savitzky-Golay filter separately for all components. The dependent variables were computed from this filtered position data.

The main focus of analyses is on the Performance Session, therefore for the Practice Session only the RMS-Error will be reported. Performance enhancement over the trials in the Practice Session is analyzed descriptively. For the constant sections as well as the random segments an exponential decay of RMS-Error is expected indicating learning. Thus an exponential function of the type $f(x)=a+b*e^{-cx}$ is fitted to each individual's data. To fit the exponential function to the data, data of the middle segment was sorted separately for RAR and RBR presentations into an ascending order of 45 presentations. For the data of the two random segments (each 90 presentations!) a mean was calculated over two consecutive presentations in steps of two, leading also to 45 values for each segment. Exponential fits, however, were only computed for presentations 16-30, because in the first 15 presentations all segments consisted of the constant section (see table 8).

Empirical hypothesis eH_{23}

Based on the secondary assumption or general hypothesis S_2 the empirical hypothesis can now be phrased (Herrmann, 1994):

> eH_{23}: In the visuomotor tracking task a competition with additional financial incentives leads to "pressure" (increase in state anxiety) and consequently to decrements in overall (RMS-Error) and turning point specific (Absolute Error) overt performance as a result of reduced covert performance (Latency)

and task exploitation (Covariation of intervals) at turning point T7 compared to the other turning points and to a no-pressure condition.

Results

Practice Session

As can be seen in figure 27 participants were able to learn not only the task but also to learn the two constant sections when they were presented in the middle segment. The RMS-Error across the two constant sections decays over the 45 trials of learning and much more than the RMS-Error when random sections were presented in segments 1 and 3. The 1-way ANOVA comparing the fitted values at the last trial of single presentation between segments reveals a significant difference between segments using Greenhouse-Geisser corrected degrees of freedom ($F(2.65,82.12)=42{,}01$, $p<.01, f=1.16$). Contrast-analyses show, that no significant difference exists between sections A and B ($F(1,31)=3{,}88$, $p>.05, f=0.35$), but between constant sections and random segment 1 (A: ($F(1,31)=28{,}04$, $p<.01, f=0.95$), B: ($F(1,31)=8{,}47$, $p<.01, f=0.52$)), and between constants sections and random segment 3 (A: ($F(1,31)=117{,}56$, $p<.01, f=1.95$), B: ($F(1,31)=87{,}78$, $p<.01, f=1.69$)). Interestingly, there is also a significant difference between random segments ($F(1,31)=41{,}57$, $p<.01, f=1.16$), with a smaller RMS-Error for random sections in segment 1.

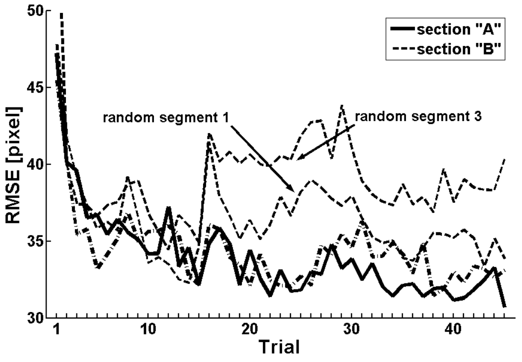

Figure 27. Description of RMS-Error for the three segments over 45 trials of learning. Note that during that in trials 1-15 all segments consisted of either section "A" or "B"

In the combined presentation (ABR/RAB) no further learning was apparent from figure 28. The mean RMS-Error for block 8 (trials 105-120) was thus compared between segments. The 1-way ANOVA reveals that RMS-Error in the random segment (R) is significantly higher than in the segments with the constant sections (AB; *F*(1,31)=31,32, *p*<.01, *f*=1.01).

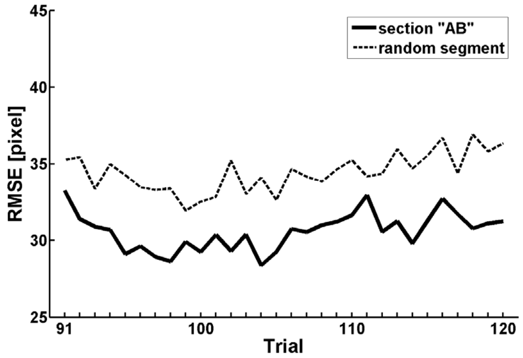

Figure 28. RMS-Error over trials 91- 120 (blocks 7 & 8) where sections A & B were presented combined.

Performance Session

For the Performance Session the RMS-Error for the entire curve was compared intraindividually between the four performance blocks (no-pressure, high-pressure, high-pressure, no-pressure) with a 1-way ANOVA with 4 repeated measurements. Turning point specific measures of overt performance (AE), covert performance (Latency) and task exploitation (Covariation) was compared with a 4(blocks) x 6 (turning points) ANOVA with repeated measures on both factors.

Manipulation Check

In order to assess the effectiveness of the pressure manipulation in the High-Pressure block, the change in level of state anxiety (measured with the STAI (Laux et al., 1981) from Warm-up to the High-Pressure blocks was compared. Although there was a small increase from *AM*=41.00 (*SD*=6.43) to *AM*=41.75 (*SD*=7.78), a 1-way ANOVA with repeated measures revealed no significant increase in the level of anxiety in the High Pressure blocks (*F*(1,27)=0.46, *p*>.05, *f*=0.14).

Performance measures

For overall (overt) performance in the four blocks of the Performance Session – measured by the RMS-Error over the entire curve – a significant difference was found between blocks (*F*(2.38,71.33)=19.92, *p*<.01,*f*=0.81). Participants showed better performance, that is more accuracy, in the pressure blocks (see figure 29).

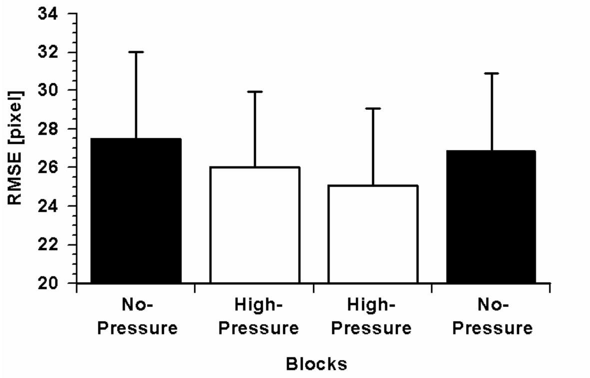

Figure 29. Overt performance in the Performance Session: RMS-Error across the entire curve (all 3 segments).

It was further evaluated, whether it would be worth analyzing only participants that performed worse under pressure. The performance in the No-pressure and the High-Pressure blocks was first pooled, respectively. But only 2 participants showed performance decrement between No-Pressure blocks to High-Pressure blocks. Also the correlation between anxiety scores and RMS- Error were examined. To this end, first difference scores were computed. A non-significant negative correlation of *r*=-.30 was found indicating that the more increase in anxiety score the more participants could reduce the RMS- Error.

To assess turning point specific performance, performance at the first, the mean over the intermediate turning points and at the last turning point of the two sections were analyzed. As can be seen from figure 30 Absolute Error at the turning points matched the results for the RMS-Error over the entire curve: Participants were significantly more accurate in the two High-Pressure blocks than in the No-Pressure blocks (*F*(2.24,60.35)=26.44, *p*<.01,*f*=0.99). There was also a significant main effect of Turning Point (*F*(3.47,93.72)=2.65, *p*<.05,*f*=0.31), but no significant interaction (*F*(7.79,210.41)=0.72, *p*>.05,*f*=0.16). Closer inspection of the Turning points shows that there is a significant contrast between Turning Point T6 against all others across all blocks(*F*(1,27)=16.97,*p*<.01,*f*=0.79).

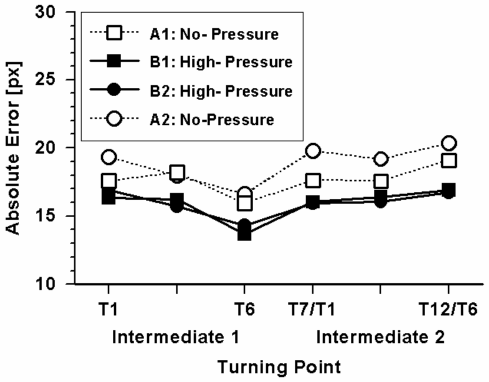

Figure 30. Turning point specific overt performance: Absolute Error from target cross at turning points.

Analysis of Latency between target and pursuit turning points also revealed a significant main effect of Block (*F*(2.43,65.67)=7.08, *p*<.01,*f*=0.51), but no significant effect of Turning Point (*F*(3.77,101.87)=0.49, *p*>.05,*f*=0.14) and no significant interaction (*F*(9.13,246.41)=1.13, *p*>.05,*f*=0.22). From figure 31 it can be seen that Latency decreased over the four blocks, but independent of the pressure manipulation. Closer inspection reveals a significant contrast between the A2: No-Pressure block against all others across Turning Points (*F*(1,27)=12.7, *p*<.01,*f*=0.69). There is no significant contrast between Turning Point T7/T1 against all others (*F*(1,27)=1.22,*p*>.05,*f*=0.21), even if Block A2: No- Pressure is removed (*F*(1,27)=1.63,*p*>.05,*f*=0.25).

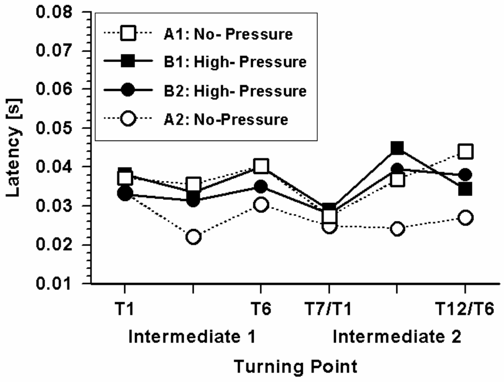

Figure 31. Turning point specific covert performance: Latency between target and pursuit cross at turning points.

Covariation at Turning Points (figure 32) showed no significant effect of Block ($F(2.26,60.93)=0.38$, $p>.05$, $f=0.12$), but a medium effect of Turning Point, which was not significant using Greenhouse-Geisser corrected degrees of freedom ($F(3.88,104.76)=2.35$, $p=.06$, $f=0.29$). There was also no significant interaction (Blocks x Turning Points: $F(7.99,215.78)=0.54$, $p>.05$, $f=0.14$).

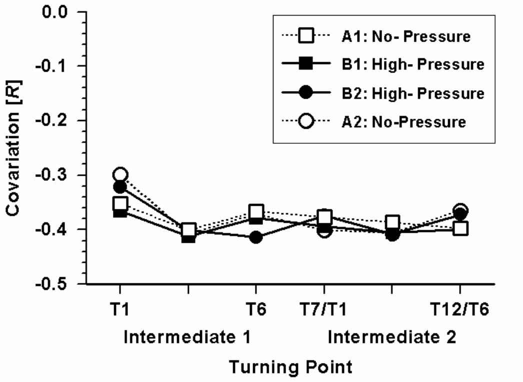

Figure 32. Turning point specific task exploitation: temporal covariation between successive intervals at turning points.

Discussion

This experiment was based on two assumptions: (1) Performers "choke" under pressure and this choking results from an explicit monitoring of the execution of the performed motor skill (cf. Beilock & Carr, 2001). (2) Explicit monitoring or an internal focus of attention leads to the control of prominent nodalpoints and to reduced task exploitation at that nodal point. Prominent nodalpoints should evolve at the concatenation of two movement sequences. Consequently it was hypothesized in this experiment that participants in the pressure situation should show poor overall performance due to reduced Covariation at the point of concatenation (turning point 7). Results first of all showed that similar to previous studies using the visuomotor tracking paradigm, participants in this study were not only able to learn the task but were also able to learn the constant sections of the curve. After first learning them separately (with randomly chosen sections in the outer segments) apparently no further learning occurred once the two sections were concatenated and only one random section either preceded or followed the combined sections. In the Performance Session, which followed the Practice Session within approximately 24 hours, participants not only maintained their previous level of performance in the pressure situation but also in fact could increase performance: Participants entered a small competition and contrary to the hypothesis eH_{23} were significantly more accurate in following the target cross than in the No-Pressure trials that preceded and followed the pressure situation. This enhancement of overall overt performance (reduced RMS-Error) is reflected by overt performance at the turning points (here: AE). Participants are very accurate at staying close to the target cross at the turning points. Interestingly, across all blocks, they are especially accurate at the last turning point of the first constant section. No differential effect of the pressure situation on covert performance was found: Instead, a sequence-effect seems to occur such that participants are "tuning into the rhythm" over trials because the latency between target and pursuit turning points decreases across blocks. Thus it appears as some learning of the task occurs even in the Performance Session. Latency, the time between turning of target and pursuit cross, is thought to be an indicator whether performers are using visual feedback to control the movement. The more time passes between the events the more performers are relying on visual feedback. The reduced latency in the later trials thus may be interpreted as a shift towards feed-forward control. However, turning of the pursuit cross still occurs *after* the target cross. Finally, no effects of the pressure situation on task exploitation were found: Covariation of the intervals between turning points occurred at the same level across all blocks and it was only slightly reduced at the first turning point of the first constant section.

As in Study 1, the formalized approach by Herrmann (1976) of the formation of hypotheses from core assumptions of the underlying theoretical concepts will be used as a frame for discussing these results. As a first step, from a methodological viewpoint it must be investigated whether the experiment was adequately implemented to test the empirical hypothesis. Of course it must first be asked whether the pressure manipulation was successful. From the results of the State Anxiety Inventory (Laux, et al., 1981) it seems that this was not the case. Participants did not report a higher level of anxiety after entering the one-on-one competition. However, since overt performance significantly changed in the pressure block, "something" must have happened. Thus it seems that pressure might have increased but participants may not have perceived it as aversive or may simply have been reluctant to report the experience of stress. Secondly, it can be speculated that two sequence effects are responsible for the performance results: Participants may still be learning the task and the underlying structure, as evidenced by increased performance across the first three blocks in the Performance Session. This is corroborated by the fact that Latency is progressively reduced in these blocks. This learning effect may be overlapped by a fatigue effect which results in poor performance in the last block (A2). Also in the last Block (A2), participants may not have put much effort in performing well since there was no reason or incentive for them to perform well.

Concerning the validity of the secondary assumptions, similar to Experiment 1, it must be asked whether the pressure situation actually lead to "explicit monitoring". This is highly questionable since participants apparently did not experience pressure. Also from the decreased Latency it may even be speculated that participants relied more on "automatic" execution through feed-forward control. Further, as argued in Study 1, explicit monitoring and therefore choking may depend on explicitly available and verbalizable knowledge about the task. Since this same visuomotor tracking paradigm is used to investigate implicit learning it is probable that participants did not accrue explicit knowledge.

In a second experiment using the same paradigm these questions should be addressed. In this experiment a between-subject design should be used in which the performance of an experimental group in a pressure situation is compared to the performance of a control group in a regular non-pressure situation. This pressure situation should also be similar to pressure manipulations in other studies on the phenomenon of "choking under pressure" (e.g. Beilock & Carr, 2002) in which a fake competition is used. This manipulation was also at least partly successfully used in Study 1. Thirdly an effort should be made to measure the amount of explicit knowledge of the participants and to evaluate whether explicit monitoring occurs.

Experiment 4

The main aim of Experiment 4 was to replicate findings from Experiment 3 in a between-subject design. But based on the discussion of the results also additional changes were applied to the experimental design: As mentioned, Experiment 4 compares performance between a no-stress control group and a experimental group performing in a stressful situation. Contrary to Experiment 3 the pressure situation in Experiment 4 also is not designed as a real competition but rather uses conventional experimental methods to manipulate stress used in previous studies (e.g. Beilock & Carr, 2002, Study 1 of this dissertation) in which a fake competition is used. Furthermore it is evaluated how much explicit knowledge about the task is accrued during the experiment and whether performers in the stress situation use an explicit monitoring strategy. Lastly, to increase the uncertainty of continuation at the concatenation, the second constant segment was not learned separately. Rather it was presented in combination with or succession to the first constant segment only after this was sufficiently learned.

Methods

Participants

42 participants were recruited for this study. The 22 female and 20 male participants (age 21-34) were all sport science students. Participants received extra credit in an undergraduate class as compensation for participation. All participants were given the 5 Euro offered in the competition (see below). The participants were informed about the experimental procedure and signed a consent form. One participant did not appear for the Performance Session on day 3, three participants did not show accurate enough performance at the end of the Practice Session (performance more than 2 SD from sample mean) thus their data was also discarded. This results in a final sample of N=38 participants.

Task and apparatus

A modified version of the tracking task from Experiment 3 was used. Participants again had to follow a target cross moving on a computer screen with a pursuit cross that they were manipulating using a digitizing tablet (AIPTEK Hyperpen). The target cross moved on an invisible curve which consisted of a start and a stop position and three segments of equal length. For each segment a section of 6 turning points was chosen from a set of 30 possible sections (see experiment 3). Over the course of learning a single section was repeatedly presented as a constant section in the middle segment of the curve. This should lead to learning of this section, which was later combined with another section to form a combined section. In Experiment 4, a higher sampling frequency of 40 Hz was chosen. Also, a tone judgment task was included similar to the tone judgment task in Experiment 2, using a prompting-technique developed by Gray (2004) to test the focus of attention of participants. A tone of 80 ms duration was presented at a randomly chosen turning point. This tone was either low-pitched (blocks 9 & 10: 300 Hz, block 11: 500Hz) or high-pitched (blocks 9 & 10: 350 Hz, block 11: 550Hz). Different pitches were chosen to avoid learning effects. After the completion of a trial participants were verbally given a prompt randomly chosen from 3 options: "direction", "pitch" or no prompt. As response to the "direction" prompt participants had to tell whether the tone occurred during an up-down or down-up movement at a turning point. The response to the "pitch" prompt was to tell whether the tone presented was the high- or the low-pitched tone. When no prompt was given, participants were instructed that no response was required. Each of these three prompts ("direction", "pitch" or no prompt) was presented 5 times during a block of 15 trials. In addition to the direction/pitch judgment, participants were also asked to rate the certainty of their decision on a 4-point scale from 1 (uncertain) to 4 (absolutely certain). This was introduced to have a more fine grained measure in which also more variance was expected. According to Gray (2004), explicit monitoring should be indicated by fewer errors to the direction and more errors to the pitch-prompt. Matching effects were expected for certainty ratings. To assess the level of state-anxiety the state version of the State-Trait-Anxity Inventory (Spielberger, Gorsuch & Lushene, 1972) was applied.

Procedure and experimental conditions

The experiment consisted of three sessions performed on three days, two practice sessions and a performance session, respectively, with approximately 7 days between sessions (period 1: 6.65 d ± 1.99; period 2: 6.83 d ± 2.21). After the participants were positioned in front of the screen they were given details about the task, specifically they were asked to constantly and accurately follow the target cross with the pursuit cross. They were not given information on the underlying regularities of the trajectory (i.e. the constant sections) that the target cross followed. In Practice Session 1, participants completed 5 blocks of 15 trials, each trial lasted 19 s. Immediately after trials a text appeared on the screen for 2 s which displayed a score giving the RMSE (in pixel) across the trial. Participants were informed that this number represented the average deviation from the target and that over practice, they should try to reduce this number. In between the blocks there was a 3 to 5 minute break in which participants could take a rest. In the Practice Session 1, one single section ("A") was presented in Blocks 1 to 4 (=60 trials) in the middle segment 2. In Block 5 a second section ("B") was added to the first section to form a constant combined section ("AB"). After 5 initial trials of single presentation (RAR) ten trials of this combined presentation (ABR/RAB) followed, with the order (ABR/RAB) permuted interindividually. In the Practice Session 2 participants completed again 5 blocks of 15 trials. In Blocks 6 and 7, the single section "A" (RAR) was presented in the first ten trials and the combined section (ABR/RAB) was presented in trials 11-15. Block 8 was a "catch" block, in which also in the middle segment a randomly chosen section was presented (RRR). Block 9 and 10 consisted each of 15 trials with combined sections (ABR/RAB). In Block 10 no performance feedback was given. After the Practice Session participants were randomly assigned to a No-Stress control group or a High-Stress experimental group. Groups were matched based on their performance (mean RMSE) in Block 10.

Finally, the Performance Session consisted of a Warm-up Block of 7 trials (4 RAR, 3 RBR) in which performance feedback (RMSE) was given after every trial, followed by Block 11 with 15 trials after which no feedback was given. Before each of the two blocks participants filled out the German version of the State-Trait-Anxiety Inventory (STAI, Spielberger, Gorsuch & Lushene, 1970; German: Laux, Glanzmann, Schaffner & Spielberger, 1981) to assess the current level of state anxiety. Before Block 11 participants in the No-Stress control group were told to „show, how much you learned yesterday!“ and asked to accurately follow the target cross. For the High-Stress experimental group a similar manipulation as was used as in experiments 1 and 2 (see also Beilock & Carr, 2002; Gray, 2004). Participants were told that (1) they were to enter a competition for which they had been teamed with another participant of this study. If both team-mates could raise their performance by 15% in the next block of 15 trials compared to their individual average performance in Block 10, each would be rewarded 5 Euro. (2) However, if one of them could not raise his or her performance, their team-mate would not receive the reward either. (3) On a posted list where already (bogus) results were marked they were then shown who they had been teamed with. (4) On this list they could see that their team-mate had already successfully raised his/her performance by 15%. Participants were always teamed up with a participant of the opposite sex. Upon completion of Block 11 participants in the High-Stress group were asked whether they had believed the fake competition story, the open answer was rated on a 4 –point scale from 1 (not at all) to 4 (completely).

Table 9. *Description of the procedure and succession of presentations of sections "A" and "B" in Experiment 4.*

		trials	Presentation	Feedback (RMSE)
Practice Session 1	Block 1	15	RAR	yes
	Block 2	15	RAR	yes
	Block 3	15	RAR	yes
	Block 4	15	RAR	yes
	Block 5	5	RAR	yes
		10	ABR/RAB	yes
Practice Session 2	Block 6	10	RAR	yes
		5	ABR/RAB	yes
	Block 7	10	RAR	yes
		5	ABR/RAB	yes
	Block 8	15	RRR	yes
	Block 9	15	ABR/RAB	yes
	Block 10	15	ABR/RAB	no
Performance Session	Warm-Up	4	RAR	yes
		3	RBR	yes
	Block 11	15	ABR/RAB	no

Dependent variables

The same dependent variables were assessed in Experiment 4 as in Experiment 3. Overt performance in the tracking task is measured by the root mean square error (RMSE), which measures the average deviation of the pursuit cross to the target cross over the entire curve. Performance at the turning points was analyzed in more detail. Overt performance at a nodal point was measured by the 2-dimensional Absolute Error (Hancock, Butler, Fishman, 1995) of pursuit- turning points from target-turning points within a block of trials. Covert performance at a nodal point was measured by Latency of turning. Latency was measured by the temporal difference between pursuit- turning points and target-turning points, with positive values indicating that the pursuit cross was following the target cross. Finally, task exploitation at a nodal point was measured by the temporal covariation at a turning point within a block of trials (see explanations above).

For the analysis of these performance measures at the turning points, only the performance at turning points within the two constant sections was analyzed. Furthermore, of the turning points, only the performance at the first and the last turning point of a section was of interest. Therefore intermediate turning points 2-5 within a section were collapsed to intermediate 1 and intermediate 2 turning points (see figure 26).

Analyses

The root mean square error of the pursuit to the target cross was computed based on raw position data across all three segments and excluding the start- and stop- segment. For further analyses the raw data was first resampled to an exact duration of 19s and an exact sampling frequency of 40 Hz. Position data was then filtered with a digital Savitzky-Golay filter separately for all components. The dependent variables were computed from this filtered position data.

The main focus of analyses is on the Performance Session, therefore for the Practice Session only the RMSE will be reported. Performance enhancement over the trials in the Practice Session is analyzed descriptively. To test whether participants had actually learned the constant section “A”, RMSE of segment 2 in Block 7 (trials 91- 100) was compared to RMSE of segments 1 and 3 in Block 7 and RMSE of segment 2 in Block 8 (which consisted of randomly chosen sections). Also, performance of the combined sections in the Practice Session was tested. To this aim, the mean RMSE in Block 9 (trials 121-135) for the combined presentation were compared with the mean RMSE for the random segment (1-way ANOVA with section/segment as repeated measure).

Empirical hypothesis eH_{24}

Based on the secondary assumption or general hypothesis S_2 the empirical hypothesis can now be phrased (Herrmann, 1994):

> eH_{24}: In the pursuit tracking task a competition with additional financial incentives leads to “pressure” (increase in state anxiety)

> and consequently to decrements in overall overt performance (RMSE), but also to reduced overt performance (Absolute Error), covert performance (Latency) and task exploitation (Covariation of intervals) at turning point T7 compared to the other turning points and to a no-pressure condition.

Results

Practice Session

Visual inspection of the learning curves of the three segments in figure 33 suggests no specific learning of section "A" in segment 2 beyond just learning the task. Statistically this was evaluated by comparing the RMSE in the three segments in blocks 7 and 8 with a 2 (blocks) x 3 (segments) ANOVA. This analysis shows a significant interaction (block x segment: *F*(1.81,66.89)=12.11, $p<.05$, *f*=0.57).

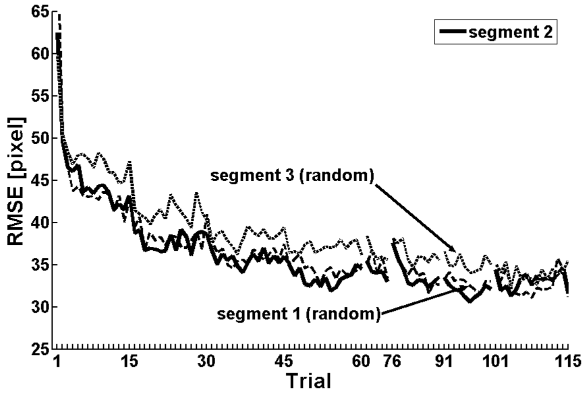

Figure 33. Description of RMS-Error over Blocks 1-8. Note that in trials 101-115 (Block 8) all segments contained randomly chosen sections.

Because figure 34 and table 10 indicate only small differences in performance of segment 2 between Blocks 7 and 8 although segment 2 was constant in block 7 but random in block 8, these two segments were contrasted. There was no significant difference (*F*(1,37)=2.29, $p>.05$, *f*=0.25) between performance in segment 2 in Block 7 (constant) and Block 8 (random).

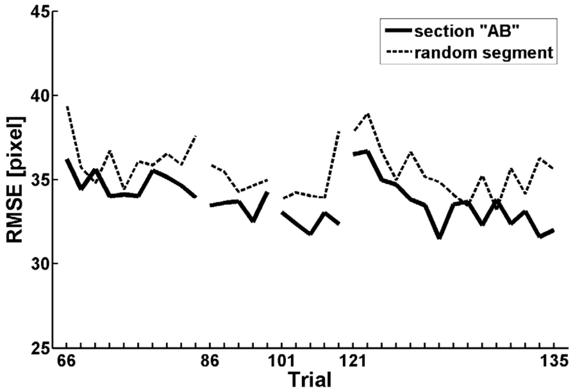

Figure 34. RMS-Error across combined sections in the AB-Presentations of Blocks 5, 6, 7 & 9.

Table 10 *Means and Standard Deviations of RMSE of the three segments in Blocks 7 and 8. Note that segment 2 in Block 7 was a constant section, in Block 8 a random section.*

	Block 7	Block 8
Segment 1	33,15 ± 6,96	32,29 ± 6,18
Segment 2	31,93 ± 6,21	32,88 ± 6,39
Segment 3	35,26 ± 6,55	33,7 ± 6,03

In the combined presentation (ABR/RAB) no further learning was apparent from figure 34. The mean RMSE for block 9 (trials 121-135) was thus compared between segments. Although mean RMSE is higher for the random segment (34.18 ± 6.47) than for the two segments with the combined sections (33.38 ± 5.95), a 1-way ANOVA reveals that this difference is not significant ($F(1,37)=2.21, p>.05, f=0.24$).

Performance Session

"Performance under pressure" was analyzed in a mixed design with the experimental groups as the between subjects factor and performance in Blocks 10 and 11 as the repeated measure. Turning point specific performance was compared with a 2 (groups) x 2(blocks) x 6 (turning points) ANOVA with repeated measures on the last two factors.

Manipulation Check

In order to assess the effectiveness of the pressure manipulation two measures were analyzed. First, the change in level of state anxiety between Warm-up block and block 11 was compared. As Table 11 indicates, an increased level of anxiety was found before the block 11 for both groups (main effect of block: $F(1,33)=14.10$, $p<.05$,

f=0.65) and no significant interaction was found ($F(1,33)=1.11$, $p>.05$, f=0.18). Secondly, it was analyzed, whether participants in the High Stress group were convinced they had entered a true competition. Answer from 17 partipants were available of whom 7 participants were completely convinced, 8 appeared to have some doubts, 2 were quite doubtful. Although the pressure manipulation may not have been successful with the latter 2 their data was not excluded from analysis because they showed increases in the state-anxiety level of 4 and 5 points.

Table 11. *Means and standard deviations of STAI-state scores.*

	Test	
Group	Warm-up	Block 11
No Stress	34.31 ± 8.49	38.06 ± 7.94
High Stress	35.84 ± 7.78	37.94 ± 8.03

Evaluation of explicit monitoring

First the reliability and validity of the tone-judgment task was evaluated. Split-half reliability of judgments and ratings was assessed in block 10. As can be seen in table 12, there is only moderate to low reliability. The very low reliability for the pitch judgment could be due to a ceiling effect: participants make almost no errors in judging the pitch of the tone. Also the statistical independence of the two prompts was assessed: there was a low (negative) correlation between errors in the two tasks (r_{tt}=-.10, $p>0.05$) but a significant positive correlation between certainty ratings (r_{tt}=.36, $p<0.05$).

Table 12. *Split-Half Reliability of the tone judgment task assessed in block 10.*

	Task	
Judgment	Pitch	Direction
- Error	.19	.49
- Certainty	.50	.56

To evaluate the focus of attention in Blocks 10 and 11 error rates and ratings of certainty in the tone judgment task were compared. A 2 (Groups) x 2 (Blocks) x 2 (Tasks) ANOVA with repeated measurements on the latter 2 factors was computed for error rate as well as for certainty-ratings. As can be seen in figure 35, participants committed fewer errors in judging the pitch of the tone than in judging direction of movement during tone occurrence, although this main effect was not significant (Task: $F(1,35)=3.21$, $p>.05$, $f=0.30$). The specific expectation was that fewer errors would occur in judging direction of movement for the High-Stress Group in Block 11. However, the 3-way interaction (Group x Block x Task) was not significant ($F(1,35)=0.01$, $p>.05$, $f=0.0$). For the certainty of the judgment, it can be seen from figure 35 that participants are generally very certain about their decisions. As for judgment error the expected 3-way interaction (Group x Block x Task) was not significant ($F(1,35)=2.40$, $p>.05$, $f=0.26$). Yet looking only at Block 11 a significant interaction (Group x Task) was found ($F(1,35)=9.37$, $p<.05$, $f=0.52$). Participants in the Stress Group are more certain in the "pitch"-task than in the "direction"-task, while the No-Stress Group shows no such difference.

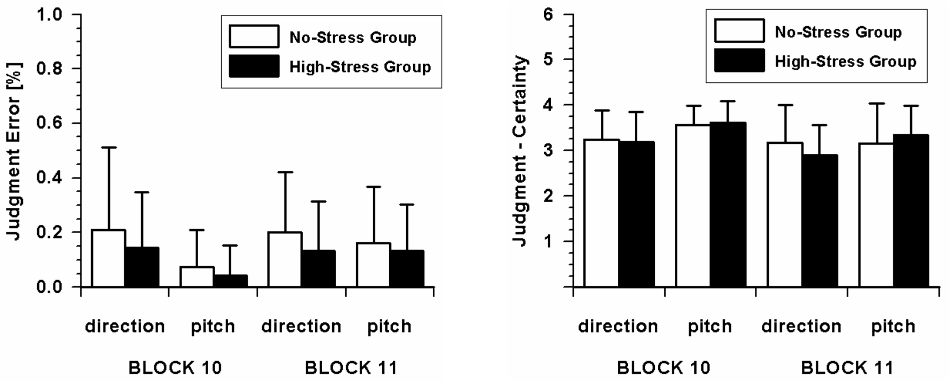

Figure 35. Tone Judgment Task: % Errors in judging direction of travel of racket and pitch of the tone presented (left) and ratings of certainty about judgments (right, scale range was from 1-4).

Evaluation of explicit knowledge

Two raters first independently found preliminary categories for all of the participants' answers (N=97). In a discussion, 5 mutual categories (see table 13) were defined based on these preliminary categories.

All answers were again classified by the two raters based on the new category system. Ratings deviated from another in 28 cases. In a second round of discussion, 10 deviating ratings were defined as errors and corrected. 12 further answers could be classified by a mutual decision, for 6 answers no such decision was reached. All an swers

Table 13. Category system for classification of the explicit rules.

#	Category description	Prototypical answer	N	%
1	Pattern – within curve	"Curves were sinusoidal up-and-down"	17	18
2	Pattern – across curves	"There were two curves, they kept alternating"	47	49
3	Performance	"I got better"	13	14
4	General execution	"I often mistook the target cross as the pursuit cross"	12	13
5	Rest		2	2

classified by any of the two raters as belonging to category 2 ("pattern – across the curves") were again rated whether they referred to start/stop phase of the curve ("start was up, stop was down" - 18.5% of category 2 answers), to unspecific mentioning of a pattern ("I learned to anticipate" – 48,2% of category 2 answers) or to a precise specification of a pattern ("There were two curves, they kept alternating" - 33.3% of category 2 answers).

The more detailed inquiry yielded the following results: After being told, that the curve consisted of a number of segments, of the 41 original participants 21 (=51.2 %) answered that the curve consisted of three or four segments, 4 (=9.8 %) had seen less than three segments, 11 (26.8 %) had seen more than four segments and 5 (12.2 %) participants gave no answer. After learning that the curve had consisted of three segments (plus start/stop) only 15 participants (=36.5%) now knowing, this appeared plausible. When being asked, which of these three segments had been constant over the last 45 trials, only 5 participants (=12.2%) correctly identified the two constant segments. Only 7 (=17.1%) answered they thought this was plausible.

Lastly the expectation put forward by the reinvestment hypothesis (Masters and Maxwell, 2004) was tested, that the more explicit rules are reported the more should participants focus on movement execution and consequently be more certain of their judgment in the pressure situation. Table 14 shows correlations divided by Stress Groups: negative correlations are found for the No-Stress Group for both tasks, but positive correlations for the High-Stress Group for both tasks as well.

To evaluate turning point specific performance, performance at the first turning point, the mean over the intermediate turning points and at the last turning point of the two sections were analyzed with a 2 (Groups) x 2 (Blocks) x 6 (Turning Point) ANOVA with repeated measures on the last two factors. As can be seen from figure 37 Absolute Error at the turning points matched the results for the RMSE over the entire curve: Participants in the High-Stress Group were significantly more accurate at the turning points in Block 11 than participants in the No-Stress Group (*F*(1,36)=15.16, *p*<.01,*f*=0.65). There was no significant 3-way interaction between Groups, Blocks and Turning Points (*F*(3.97,142.84)=0.36, *p*>.05,*f*=0.01).

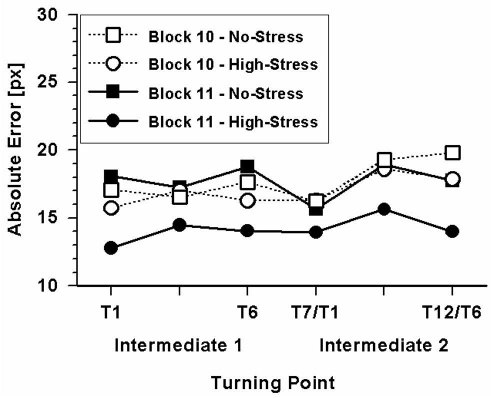

Figure 37. Turning point specific overt performance: Absolute Error from target cross at turning points.

Analysis of Latency (figure 38) between target and pursuit turning points revealed no significant interaction between Groups and Blocks (*F*(1,36)=0.02, *p*>.05,*f*=0.0). There was also no significant 3-way interaction between Groups, Blocks and Turning Points (*F*(3.80,136.89)=1.41, *p*>.05,*f*=0.20). A closer inspection of Latency at turning point 6 also did not reveal a significant interaction between Blocks and Groups (*F*(1,36)=1.77, *p*>.05,*f*=0.22).

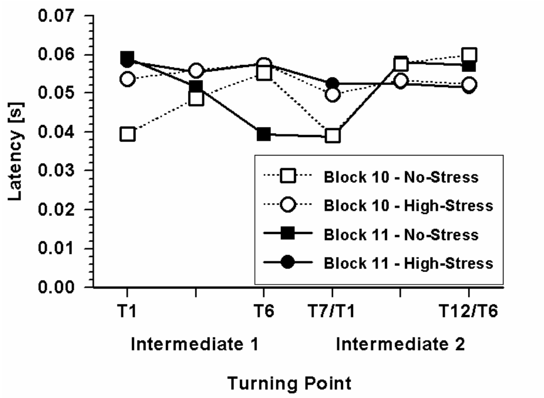

Figure 38. Turning point specific covert performance: Latency between target and pursuit cross at the turning points.

Figure 39 shows results for Covariation at Turning Points. The statistical analysis revealed no significant 2-way interaction (Groups x Blocks: *F*(1,36)=0.38, *p*>.05,*f*=0.10) and no significant 3-way interaction (Groups x Blocks x Turning Point: *F*(3.44,123.66)=0.45, *p*>.05,*f*=0.11).

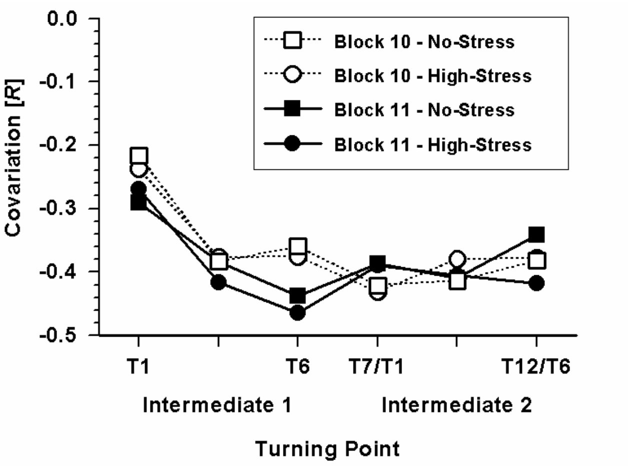

Figure 39. Turning point specific task exploitation: temporal covariation between intervals at turning points.

Discussion

Contrary to the underlying core assumption, no choking under pressure was found in this experiment, corroborating findings in Experiment 3. Participants in the Stress Group performed better in the final Block 11, where they entered a fake competition, compared both to their individual performance in the preceding Block 10 (without pressure) and to performance of the non-stressed Control Group. This overall enhanced overt performance under pressure is accompanied by a turning point specific increased accuracy but not increased covert performance or task exploitation. There was also no specific effect of the turning point 7 at concatenation of the two segments. Analysis of the verbal protocol reveals that although participants' performance in the constant segments is better than in the random segment they only seem to notice some pattern across the trials but they are not able to verbally explain the underlying structure or regularity of the curves. From the tone judgment task no evidence for increased explicit monitoring in the pressure situation could be derived. In fact, because they were less certain about the direction-judgment than about the pitch-judgment, it appears that participants in the Stress Group did not focus on the movement as much as on the tone.

From a methodological viewpoint it must be criticized that similar to Experiment 3, the pressure manipulation in Experiment 4 appears not to have been successful. Participants in the Stress Group do not report higher anxiety scores in the pressure situation than participants in the non-stressed Control Group. Again, it may be discussed whether participants may not have reported their level of stress because of two observations: First, the Stress Group must have been impressed in some way, because it significantly performed better than the Control Group. And secondly a pressure manipulation was used, that has been used successfully to induce choking in previous studies. Still, the lack of "pressure" may explain why participants showed no explicit monitoring and also no choking. It is worth noting, however, that the tone judgment task may after all not be a good test to evaluate explicit monitoring, at least the way it was applied in this experiment. First of all, split-half reliability was shown to be rather low, for both errors as well as certainty ratings. Secondly, participants made almost no errors in the two tasks and there was also only small variance in the ratings. And lastly, the intercorrelation between the tasks was not as expected: If a small error score in the pitch judgment indicates an "internal focus" and a small error score in the direction judgment is indicative of an "external focus" then the two scores should be negatively related. For the error scores this was only marginally (r=-.10) the case, but the certainty ratings were even significantly positively related! Thus the tone judgment may rather measure "concentration" than the focus of attention. Unfortunately Gray (2004) did not report any measures of reliability or validity in his original work, so it cannot be decided whether this is a general problem of the tone judgment task or just a problem of its application in this experiment.

Summarizing again briefly before the general discussion, Experiment 4 was able to replicate the finding from Experiment3, that in a visuomotor tracking task no choking under pressure was found. Participants do not seem to accrue much explicit knowledge about the underlying task structure, and in the pressure situation they also do not seem to explicitly monitor the task. Finally, there is no evidence that the uncertainty of continuation at the concatenation was increased by not presenting the second constant segment in a single presentation.

General Discussion of Study 2

The search for a mechanism on sensorimotor level that could explain the phenomenon of choking under pressure was defined as the cardinal question of this dissertation. The analysis of existing work yielded not only a call for an analysis of movements on different levels of analysis but also for a theory that could be proved for such a mechanism. This theory was found in the nodalpoint hypothesis of motor control (Hossner & Ehrlenspiel, 2006) which was "imported" into the research program concerned with the phenomenon. The nodalpoint hypothesis assumes a sequence of nodalpoints as the control structure of movements. It suggests that "explicit monitoring" or an "internal focus of attention" – which have been argued to underlie the phenomenon of choking under pressure (e.g. Beilock & Carr, 2001) – is linked to the "control" of such a nodalpoint. It consequently makes two key predictions: Explicitly monitoring or internal focusing results in (1) reduced exploitation of task space, and more specifically (2) this reduced exploitation occurs at the nodalpoint in focus. The aim of Study 2 was to examine the second of the key predictions. To this aim participants learned and performed a fairly simple motor skill of visuomotor tracking of a target on a computer monitor. The target followed an invisible curve which consisted of three segments. Each segment consisted of six turning points. Participants learned two successive (constant) segments of the curve, while one segment was random across the experiment. Performance in the task was evaluated on three levels of analysis: overt performance, as measured by overall RMS-Error of the pursuit cross to the target and turning point specific Absolute Error, covert performance, the turning point specific latency between target and pursuit cross, and task exploitation, the covariation between intervals between turning points. It was hypothesized that (1) participants in a pressure situation should show decrement of performance on an overt and covert level (2) due to reduced exploitation of task space under pressure. Surprisingly, but interestingly matching results from Study 1, in this study no choking under pressure was found. Participants who entered a real and a fake competition performed better in these pressure situations compared to an individual baseline performance and/or to participants who continued the experiment without adding pressure to the situation. Clearly, with this result the cardinal question about the mechanism behind choking can not be answered – because there was no choking after all!

The general discussion of Study 2 can follow along the same line used for discussing Study 1 – thus both experimental as well as more "deeper" concerns about the general hypotheses will be discussed with regards to the situation, the person and the task. Of course it has to be asked with respect to the situation whether the experimental manipulations were effective. From viewing self-reported levels of anxiety it appears that neither the real nor the fake competition were appropriate to have participants experience "something being at stake". Still and again, it must be argued that (a) at least the manipulation used in Experiment 4 has been used in other studies before to elicit choking (cf. Beilock & Carr, 2001) and (b) that participants did react to the change in the situation: they performed better! Yet there is no evidence that participants tended to explicitly monitor the task in the pressure situation – as was expected from the core assumptions and previous studies (Gray, 2004). This may of course be due to the lack of pressure but it may also be due the lack of explicit knowledge of the task performed (cf. Masters, 2000). Participants appear to implicitly learn the task, because they are not able to verbally express any knowledge about the task structure, despite the fact that they are effectively executing it.

This leads to a further scrutinizing of the task: Contrary to the ball bouncing task the visuomotor tracking task bears some more complexity as it involves finer grained eye-hand-coordination in the plane and in time. Participants also need more trials to learn the task. Viewed against the Bond and Titus (1983; Strauss, 2002) background this task should be more prone to choking. But the tasks also share some properties, since overt performance is assessed qualitatively (by accuracy) and they are both continuous in nature. In the discussion of Study 1 it was argued that in such tasks, less time is spent on planning and more time is available for applying action- control strategies to overcome pressure and explicit monitoring during task execution. Consequently in continuous tasks no explicit monitoring and no choking may emerge.

General Discussion

Choking under Pressure – What have we learned?

Table 14 *Correlation coefficients between number of rules ("explicit knowledge") and judgment certainty in the tone judgment tasks ("explicit monitoring").*

	judgment certainty (in Block 11)	
Number of rules reported by…	direction	pitch
No-Stress Group	-.44	-.37
High-Stress Group	.36	.29

Performance measures

For overall (overt) performance in the blocks 10 and 11 - measured by the RMS-Error over the entire curve – a non-significant interaction was found between blocks and groups (*F*(1,36)=4.13, *p*=.05,*f*=0.34). Still, participants in the Stress Group showed better performance in block 11, i.e. in the fake competition (see figure 36).

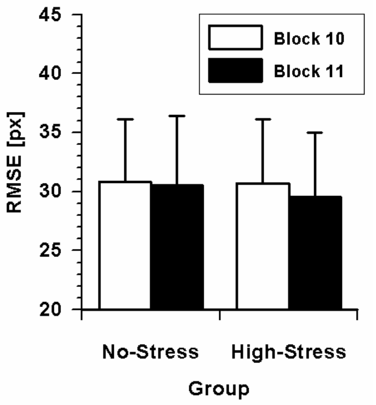

Figure 36. Overal overt performance: RME-Error across the entire curve.

It was further evaluated, whether it would be worth analyzing only participants that performed worse under pressure. But only 3 participants of the High-Stress Group yet 6 participants of the No-Stress Group showed performance decrement between blocks 10 to 11. Also the correlation between anxiety scores and RMS- Error was examined. To this end, first difference scores were computed between Warm-Up and Block 11 for anxiety scores as well as RMS-Error. A non-significant positive correlation of *r*=.420 was found for the No-Stress Group and a non-significant negative correlation for the High-Stress Group (r=-.15). These participants could reduce the RMS- Error the higher their increase in anxiety score.

Taken together similar to Study 1 the main problem with interpreting the results lies in the question whether the pressure manipulation was successful. It is therefore questionable whether the secondary assumptions or even the core assumptions may or need to be modified. Because of the potential lack of pressure, the assumptions that pressure leads to explicit monitoring which leads to choking and that explicit monitoring may be explained by the nodalpoint hypothesis may not have been tested after all. But if one assumes that the manipulation was indeed successful it seems fruitful to investigate more closely the tasks chosen. Thus, the two studies seen together provide for a number of points for discussion, that could advance the understanding of the phenomenon of choking under pressure.

This dissertation started out with the observation of Baggio's abysmal kick in the final of the 1994 soccer world cup and the original question: why do athletes choke under pressure? Previous research has addressed this question by investigating antecedents and conditions of choking, and it has been able to identify a number of these moderators in the pressure – performance relation. The original question was thus modified and specified to the cardinal question – how does pressure lead to choking? – and its search for a sensorimotor mechanism behind the phenomenon of choking under pressure. Because it has been shown that attentional processes in which the execution of the task is explicitly monitored are involved in this phenomenon it was assumed that the nodalpoint hypothesis of motor control (Hossner & Ehrlenspiel, 2006) could provide the theoretical basis for such a mechanism. It assumes a sequence of nodalpoints or effects of SRE-triplets as the control structure of movements. It was expected from the key predictions that if the choking-phenomenon could indeed be seen as an "intended application" (Westermann, 2001) of the nodalpoint hypothesis, then under pressure (1) reduced exploitation of task properties should occur (2) at a nodalpoint in focus. Two studies were designed to test these ideas put forward in the core assumption.

Brief Summary

Study 1 aimed primarily on the first key prediction of the nodalpoint hypothesis and did not compare different nodalpoints of a movement. But it attempted to extend the notion of task exploitation from the utilization of covariation (as in the original studies by Hossner & Ehrlenspiel, 2006) to the exploitation of dynamical stability. In a semi-virtual set-up participants learned a ball bouncing task. Previous studies have shown that learners are able to exploit its properties of dynamical stability (Sternad et al; 2001). The results of the first experiment showed – in contrast to expectations – that participants did not perform worse in a pressure situation, induced by a fake competition, but rather improved performance on all levels of analysis. It was argued that choking might not have occurred because participants did not accrue verbalizable knowledge of the task, a notion suggested by Masters (1992) who found that implicit learning prevented choking. In a second experiment half of the participants therefore received verbal instructions. In addition to evaluating the acquisition of explicit knowledge it was attempted to measure "explicit monitoring" directly via a tone judgment task, previously employed by Gray (2004). However, the results of the second experiment showed that no choking under pressure occured, even in the group that had received explicit task instructions. This group did report (slightly) more rules that also referred more to body parts and the movement rather than some general performance strategies. But no evidence for explicit monitoring in the pressure situation was found from the tone judgment task. It was discussed whether this was due to the lack of pressure because participants did not report higher levels of anxiety in the pressure situation. But it was also argued that the type of the task, especially its continuous nature may prevent choking, either by reducing pressure or reducing the likelihood of explicit monitoring. Taken together, Study 1 was not able to discover a sensorimotor mechanism behind choking, because no choking was found in this ball bouncing task.

The aim of Study 2 was to test the second key prediction of the nodalpoints hypothesis that expects the reduced task exploitation at prominent nodalpoints. Using a visuomotor tracking task, participants learned two movement segments, first separately and then combined. It was expected that under pressure attention should be directed at the point of concatenation because a relative uncertainty about continuation exists at that point (owing to the part-whole learning). This should lead to reduced exploitation of temporal covariation at that nodalpoint compared to other nodalpoints. Nodalpoints were assumed to be all the turning points of the curve underlying the visuomotor tracking task. The results of the third experiment showed – similar to the results in Study 1 – participants in this tracking task performed better in a real 1-on-1 competition than in non-pressure conditions. No particular effects at the point of concatenation were found. The discussion revealed that the results might have been due to methodological issues. First of all, self-reported levels of anxiety did not show an increase in pressure in the competition. Also, the improved performance could have been due to sequence effects. But it was also argued that participants might not have accrued explicit knowledge, preventing choking. Consequently, in a second experiment, a between-subject design was used in which half the participants entered the standardized pressure situation adopted in Study 1. Also the amount of verbalizable knowledge about the underlying structure of the task was evaluated. Furthermore explicit monitoring was assessed using a version of the tone judgment task similar to the one employed in Study 1. The results of this fourth experiment showed again that no choking under pressure was elicited. Participants generally reported only a very small amount of explicit knowledge about the structure of the task, indicating implicit learning. No evidence for explicit monitoring was found, instead results from the tone judgment task seem to indicate reduced explicit monitoring.

The four key issues

From the summary of the results and the discussion of the four experiments in the two studies of this dissertation four key issues can be identified. They concern the effectiveness of the pressure manipulation, the occurrence of explicit monitoring in the pressure situation, the role of explicit or verbalizable task knowledge in the pressure-performance relation, and finally the type of the task used to investigate the phenomenon of choking under pressure.

The pressure manipulation: Was it effective?

Pressure was defined in the Introduction as a situation in which a person perceives something being at stake depending on the outcome of one's performance. It is a clearly subjective perspective that does not depend on the presence of objective stressors. From an experimenter's perspective one can only try to add objective stressors that have been shown to raise pressure and to lead to choking. This was the approach taken in the reported experiments, with the exception of Experiment 3, that tried to closely mimic a real competition. An important feature of all experiments, however, is that the subjective experience was actually measured by using self-report anxiety scales. Other studies, prominently investigating choking did not attempt to measure whether participants did indeed feel under pressure (e.g. Beilock & Carr, 2001, Lewis & Linder, 1997) and only assumed their manipulation worked. A notable exception is the study by Masters (1992) and the subsequent studies (Hardy, Mullen & Jones, 1996) who used the Competitive State Anxiety Inventory, a sport specific measure to assess the level of state anxiety. This may indeed be a more appropriate and more sensitive measure than the State-Trait-Anxiety Inventory (Spielberger, Gorsuch & Lushene, 1970) that was used in this dissertation. On the other hand, besides the fact that this measure has only been recently translated into German (Ehrlenspiel, 2005), the problem with this measure is that it is not applicable for non-stressed control groups. Many questions refer to an upcoming competition and these cannot be answered by a control group, thereby possibly distorting results. So keeping in mind that in some of the reported experiments anxiety did rise under pressure (though not significantly), that the same manipulation has been used successfully before and, last but not least, that effects of the pressure manipulation did appear on an overt performance level, for the further discussion it will be assumed that the experimental manipulations were effective in evoking pressure.

Explicit monitoring: Did it occur?

One tenet put forward in the Introduction of this dissertation was that under pressure performers explicitly monitor the execution of their movement, i.e. they direct their attention to it. There is, however, no indication that this occurred in any of the experiments of this dissertation. At the risk of arguing somewhat circular the absence of explicit monitoring could first be inferred from behavioral data on an overt level: no choking occurred. Secondly – and still on circular grounds – on a covert and task exploitation level of analysis, no effects of the pressure situation appeared, which were expected given the nodalpoint hypothesis. Thirdly, and more soundly in Experiments 2 and 4 no effect of pressure on performance in the tone judgment task was detected. This observation strongly points to the absence of explicit monitoring notwithstanding that in the experiments' discussions it was laid out that the reliability of the task as well as its validity might be compromised. Considering a somewhat closer look and only regarding the slightly more difficult tasks – direction judgment in the ball bouncing and the judgment certainty in the tracking task – with more variance in the variables one can observe results that do speak in favor of the tone judgment task. In Experiment 2 under pressure the Stress Groups with instructions reduces its errors in direction whereas the non-instructed Stress Group increases errors. In Experiment 4 under pressure the High-Stress Group was less certain about direction judgments and more certain about pitch judgments compared intraindividually to errors in the non-stressed Block 10 but also against the No-Stress Group in Block 11. It must be mentioned that despite the apparent flaws of the tone judgment task, which concern its reliability and the independence of its dimensions, this study is one of only two that have attempted to directly assess explicit monitoring (the other being the Gray, 2004, study). All other studies have inferred explicit monitoring completely from behavior on an overt level! So, although with some care, we can assume explicit monitoring was measured but it was not found to occur in the four experiments.

Explicit knowledge: Is it relevant?

This question was really only directly addressed in Experiment 2 and from its results one could deny the importance of explicit or verbalizable knowledge. Even giving explicit instructions did not lead to choking in the ball bouncing task. But analyzing the explicit rules given by participants reveals only small differences between explicit and non-instructed groups with respect to number and content of the rules. Instructed participants do not seem to have picked up decisively more knowledge about the task than the non-instructed participants, and neither group reported any knowledge about the central variable driving stability: the acceleration at impact. In Experiment 4, participants did not pick up much explicit knowledge of the task. They did report a number of rules but these are mainly associated with general performance strategies and observations but only in very few instances with the underlying task structure. From these results it can be concluded that in all of the tasks not much explicit knowledge was accrued, and where it was, it did not lead to explicit monitoring or even choking. Still, the role of explicit knowledge in the pressure – performance relation can be further evaluated by looking at the relation between explicit knowledge and explicit monitoring. Masters (2000) clearly proposes, that the more explicit knowledge is available for "reinvestment" the more explicit monitoring should occur. This was tested by correlating the number of reported rules in the open questions of Experiment 2 and 4 with the performance in the tone judgment task in the pressure situations. The results offer two insights: The more rules are reported, i.e. the more explicit knowledge is accrued, the fewer errors are made *in the pressure situation* in the tone judgment task in Experiment 2, and the more certain about their answers are participants in Experiment 4. This clearly points to the relevance of explicit knowledge for explicit monitoring. The second insight pertains to the supposed dimensions of the tone judgment task: these correlations were found for both tasks (direction and pitch), although they should measure different aspects. Taken together conclusions about the relevance of explicit knowledge are hard to draw based on the results from the four experiments. It clearly needs more thorough investigation.

The task: Was it the right type?

Some aspects of the tasks have already been discussed earlier that might have prevented choking. These concern the "classic" properties (e.g. Bond & Titus, 1983) such as task-complexity (simple vs. complex) the performance measure (quantitative vs. qualitative) and respective motor ability (coordination vs. condition). Both tasks used in this dissertation are probably rather simple, (overt) performance is measured qualitatively by assessing accuracy and they are dependent upon coordination and not so much upon condition (see Strauss, 2002, for the latter distinctions Bös, 2001). Although empirical findings are somewhat unequivocal both Strauss (2002) in his review and Bond and Titus (1983) in their meta-analysis find that performance in simple tasks is enhanced under pressure, whereas coordinative tasks in which performance is measured qualitatively are often found to suffer from pressure. In addition to this inconclusiveness the mechanism of why either property of a task leads to choking or not are not clear, if investigated at all. These classic categories consequently do not help in understanding the results of the four experiments but it seems that a further mutual property of the two tasks, ball bouncing and tracking, is crucial: their continuous nature.

Although the ball bouncing task is comprised of repeated acts – hitting a ball to a target – that have a (fairly) clear start and goal and are therefore discrete (Magill, 1989) through their repetitive execution the movement itself is continuous and sinusoidal. In continuous movements the movement itself becomes the goal of the task, and this is the case in both the ball bouncing as well as the tracking task. As is witnessed by the rules reported to produce stable performance but also from the dynamical stability analysis, the goal in this task shifts from hitting the ball to the target on every (single) bounce to produce a steady pace and motion which by itself leads to constant and accurate performance. In the tracking task there is no other goal of the task than producing an accurate movement. Kunde and Weigelt (2005) were able to show that performance in a discrete bimanual choice reaction task was affected by goal congruency, when specific object orientations were required but a motor-symmetry effect, when the movement itself became the action goal. They interpret their finding as showing that action goals can relate to body-intrinsic or body-extrinsic states and that it is the creation and maintenance of these goal codes that task performance depends on. This can be taken further to saying that if the movement becomes the action goal then focusing attention to the movement enhances performance. In addition to the role of action goals, several aspects are also unique to continuous skills. For example, as can be seen in the open answers in the tracking task, "flow" (Csikszentmihalyi, 1990) can occur. When equilibrium between challenge and task competence (or "skill") is perceived performers dissolve in the task. Participants in the tracking tasks reported that they absentmindedly started to control the target cross but not their pursuit cross, a clear sign of being "one with the task".

Another issue concerns the duration of task execution which allows for the application of action- control strategies (Beckmann & Strang, 1992) that can be applied "online" during task execution, a strategy that is impossible in discrete tasks. Such strategies could employ self-regulation to overcome pressure and its detrimental effects or focusing. Such focusing strategies are used in applied sport psychology to maintain or enhance performance in continuous tasks such as downhill-skiing (Beckman, 1993). Moreover, in the two tasks of this dissertation there is also continuous control involved, either through passive use of stability or through visual feedback, whereas discrete tasks rely on "open-loop" control, i.e. the movement must be "programmed" or at least planned in advance. Such planning may be more susceptible to detrimental effects of explicit monitoring (in this case rather "explicit planning"). Movements could then be prepared and initiated in terms of the anticipation of body-intrinsic, or internal action effects (at nodalpoints) rather than external and final effects in the environment. In well learned skills, where usually this final effect will control the movement (in light of the nodalpoint hypothesis), the amount of time available for movement planning may moderate whether movement execution is indeed prepared in terms of the internal effects at nodalpoints under pressure.

Future directions

The four key issues in the results and their interpretation lay the ground for further investigations into the phenomenon of choking under pressure and its underlying mechanism. This research will continue to be guided by the core assumption that explicit monitoring is the mediator between pressure and performance. Because there was no explicit monitoring in the tasks reported there was no choking! This observation also means that in principle, the phenomenon still resembles a potential model (and possibly an intended application) of the nodalpoint hypothesis of motor control. The failure of the empirical hypotheses can not be attributed to the (imported) nodalpoint hypothesis but rather to failures in the transformation from core to secondary assumptions, notably by selecting inappropriate tasks. The explanations to the key issues of course need to be tested, consequently some suggestions are developed for this endeavor.

Of course, research could tackle the question of optimal experimental manipulations to induce pressure. These should not only be practicable and affordable but also they should reliably lead to the experience of "pressure". In this vein it is also important to evaluate whether participants do indeed feel under pressure by self-report measures of stress or anxiety. This has been neglected in most of the previous experiments (e.g.

Beilock & Carr, 2001; Lewis & Linder, 1997). Admittingly, it is more interesting to investigate the role of explicit knowledge and the type of task in the pressure – performance relation.

The role of explicit knowledge as a potential moderator in the pressure-performance relation needs some vigorous examination. The relevance of explicit knowledge has been proven primarily in research testing the "reinvestment hypothesis" (Masters, 2000; Masters & Maxwell, 2004). With this research first of all a number of methodological problems are connected (cf. Bennett, 2000), but also practical and conceptual. The practical problem concerns the question how the accrual of explicit knowledge in real-life settings could be prevented. The use of analogies to circumvent explicit instructions, as proposed by Masters (Liao & Masters, 2001; Masters & Maxwell, 2004) seems of only limited use. Of practical relevance also appears the fact, that in every experiment, the implicitly learning groups performed below the groups that learned with explicit instructions, even under pressure! Conceptually, there needs to be a more thorough investigation whether there are really two distinct learning processes involved that lead to different knowledge structures. Although there are many differing definitions of implicit learning (cf. Stadler & Frensch, 1998), the term "implicit learning" is often (and best, see Frensch, 1998) thought to imply the *un-intentional acquisition* of knowledge about structural relations rather than the "un-conscious" acquisition. In all of the studies in the Masters' (1992) tradition, learning was clearly intentional (although participants may not have been explicitly told to learn the task), thus not implicit in Frensch's (1998) sense. To infer implicit (or explicit) learning from the number of rules or answers given in a post-learning interview is a very crude measure. In the classic implicit learning paradigm (Nissen & Bullemer, 1987) usually generation task or at least recognition tasks are used to evaluate explicit knowledge. Additionally, often a dissociation paradigm is used, to assess whether distinct learning processes and/or knowledge structures are the basis for performance differences (e.g. Destrebecqz & Cleeremans, 2001; critically on the dissociation paradigm: Wilkinson & Shanks, 2004). Despite this criticism and the consequent doubts about differing knowledge structures in the studies investigating "reinvestment" under pressure, still the observation needs to be explained that if more "rules" can be reported then performance breaks down (notably in the Liao & Masters, 2001, study). I want to argue that the key lies in the content of the knowledge, rather than in its nature (see for similar reasoning Poolton, Maxwell, Masters & Raab, 2006). It is plausible that if more rules about the structure of a task are reported that these rules do not (only) refer to the properties of the task that are essential to successful performance. In this vein the results from a study by Shea, Whitacre, Wulf and Park (2001) were re-interpreted by Perruchet, Chambaron and Ferrel-Chapus (2003). In the original study, participants performed a visuomotor tracking task that was structured identical to the task used in Experiments 3 and 4 with three segments, one of which was constant. Shea et al. (2001) found that giving participants information about the underlying regularity, i.e. that the middle segment was constant, did lead to poor performance compared to implicit learning without such additional information. It is claimed that explicit knowledge is less effective and that implicit knowledge might be exploited more efficiently. Perruchet, Chambaron and Ferrel-Chapus (2003) argue, however, that the information given is essentially useless, because it does not refer to relevant information and directs the focus to negligible or even disturbing features. A last aspect questioning the “reinvestment” hypothesis comes from observations that actually explicit processes impair implicit learning and performance of motor sequences. Howard and Howard (2001) could show a deleterious effect of explicit processes when cognitive load is increased, for example by difficult sequences (see Fletcher et al., 2005, for further evidence from brain activity). Future studies could go two ways: It seems appropriate to take some of the sequential learning tasks for which a dissociation between explicit and implicit processes has been shown and evaluate performance therein under pressure. A second approach could distinguish the content of verbalized knowledge and the number of rules reported in this verbalization, possibly examining the focus of attention they refer to (cf. Poolton et al., 2006).

The continuous nature of the two tasks used in this dissertation seems to be the pivotal aspect that prevented pressure from leading to choking. Although the discussion also revealed differences in the tasks, the potential mechanisms discussed probably apply to both tasks. A first mechanism involves self-regulation and action- control, an aspect already discussed in the introduction regarding the contradictory findings of Beilock and Carr (2001) and Masters (1992). It is interesting that most of the studies on the phenomenon of choking have neglected the impact of such “psychological” processes on the pressure-performance relation. Because this could be a point in the relation at which applied sport psychologists could intervene by teaching self-regulatory skills. A possible way to test the importance of self-regulation as a mediator could be to first put subjects under pressure and then apply a further situation in which self-regulation is necessary such as a stressful social interaction. It has been shown that self-regulation of deplets resources which are then not available in a subsequent task, demanding further self-regulation (Baumeister, Muraven & Tice, 2000). Accordingly, Oaten and Cheng (2005) found reduced Stroop-Task performance (a measure of executive or self-control) in students preparing for an exam.

A second theme discussed concerning the continuous tasks was the lack of or brevity of the time for movement planning and preparation. The role of this pre-execution time could be tested by having subjects enter a choice reaction time (CRT-) task. For instance, subjects first learn two sequences of key presses and a valid advance cue to each sequence. In a retention test, the two sequences are cued with varying stimulus onset asynchronies (SOA) by introducing an additional go-signal to which the cued sequence needs to be executed. Choking should occur only in longer SOA conditions if it indeed depends on the availability of time for (explicit) preparation. Generally, serial reaction time tasks or similar sequence learning tasks with a sequence of discrete tasks that are not self-repeating appear to be useful for investigating choking and the predictions of the nodalpoint hypothesis. In these tasks, in contrast to the tracking task used in Study 2, it has been shown that learners are able detect and exploit varying relationships and regularities (Koch & Hoffmann, 2000). This forming chunks is usually experimentally (but only sometimes intentionally) produced through statistical or relational patterns in the learning material – for example the sequence ABCABC will most likely be grouped into ABC-ABC. But in a recent study, Kennerley, Sakai and Rushworth (2004) showed that learners also temporally structure unorganized sequences. Evidence for the formation of chunks (as opposed to a loose “grouping”) comes from transcranial magnetic stimulation (TMS). Only when TMS over the presupplementary motor area was applied at the beginning of a chunk the execution was disturbed but not when it was applied within a chunk. Similar effects (though may be not as drastic) should occur under pressure, according to the nodalpoint hypothesis. In fact, a first experiment using a sequence of key presses did find evidence for this idea, also underlying the Study 2 in this dissertation (Oberländer, Ehrlenspiel & Erlacher, 2006; cf. for details Oberländer, 2006). Participants learned two sequences of key presses, first separately, than concatenated. In a subsequent performance test, participants that entered a pressure situation produced fewer correct sequences than the non-stressed control group. This seems to be due to an increased number of errors at the first key press of the second sequence. All things considered, the sequence-learning paradigm thus proves to be vital for investigations into understanding the phenomenon of choking under pressure.

Open questions

For the understanding of mechanisms, Neumann (1992) not only demands the integration of several levels of analysis but his main claims are that it has to be determined what the function of the mechanism and the constraints under which it works are. This implies that before understanding the *why* the question of *wherefore*? has to be answered. The question about the functionality of explicit monitoring under pressure has so far been completely neglected, even in this dissertation. Why should it be functional to focus one's attention on the execution of a task, when one is feeling under pressure? Or to put it in terms of evolutionary psychology: Why would an organism profit from focusing on the task execution when its life was at stake?

Dörner (1999) has proposed a ψ-organism that he constructed strictly based on a functional analysis of (human) behavior. This organism behaves quite interesting: once in a while it halts in its stream of actions to check whether the intended action goal has already be attained (or whether it is at least still on its way to the goal) and to check the background upon which the action ensues. This behavior prevents rigidity on the one side – other, better options for action are noticed, potential threats are perceived – but also it secures the right course of actions by checking the sub-goals. When riding the train in the morning, it is quite helpful to look up from my newspaper to check every once in a while to check what station the train is just entering, if I want to get off the train at a particular station. The frequency of this checking behavior, according to Dörner (1999), is not dependent upon a strict internal clock but on a threshold, which depends on the openness of the situation and the strength of the action goal. The openness results from the interaction of the novelty or uncertainty of the situation and the perceived competence. The more "open" a situation, the more checking occurs because it secures that the intended action goal will eventually be attained. After riding the U8 in Berlin for four years, I did not have to look up from my paper at every stop – but after moving to Munich, reading the paper is much less relaxed. It is plausible to assume that such checking should occur at "prominent" nodalpoints or endpoints of action-chunks to secure that they are attained before the next step is executed. Assuming that there is such a functional aspect behind the checking of nodalpoints (or "explicit monitoring") the same behavior should appear in other similar situations, when a situation is either novel or competence is perceived as low. Effects on performance and task execution resembling choking should be expected under these conditions.

So, after all being said, what is the "take-home-message"? The cardinal question about a sensorimotor mechanism behind choking under pressure can not be answered because in the experiments no choking was found. This is apparently owing to the continuous nature of the tasks used in the studies. It can be assumed that in such tasks despite pressure explicit monitoring of the task does not occur owing for example to action- control strategies or that such tasks benefit from explicit monitoring. Finally, discrete tasks should be more susceptible to choking because during the time of action selection and planning explicit strategies may be more interfering. Concluding, it can be remarked that from this dissertation we do not know why athletes choke under pressure but there are at least some ideas why participants did *not* choke under pressure in its experiments. Unfortunately though, the initial question thus still remains unanswered: Why did Baggio miss the goal? From the results in this dissertation we can only conclude that if it had been the world cup in ball bouncing or tracking, Baggio might have had better chances to win it.

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Erklärung

Hiermit erkläre ich, dass die Arbeit selbstständig und ohne unzulässige Hilfe Dritter verfasst wurde und bei der Abfassung nur die in der Dissertation angegeben Hilfsmittel benutzt sowie alle wörtlich oder inhaltlich übernommenen Stellen als solche gekennzeichnet wurden.