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Practice variability in learning isometric hand grip

PhD Thesis

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Chapter 1 INTRODUCTION

Hand movements are inevitable parts of our lives. They are necessary for motor and cognitive development, daily living activities, education, work and social participation. Hand movements consist of two main motor components: scaling of isometric hand grip and controlling independent finger movements (Xu, Haith, & Krakauer, 2015). Isometric hand grip is a basis of stability when grasping and holding objects such as a pencil or a full teapot. This function assumes the adequate scaling of forces applied to the objects kept in the hand. On the other hand, independent finger movements play a role in manipulation with objects and partly rely on the supporting role of the hand grip function (Payne & Isaacs, 2012). While learning of independent finger movements gained a lot of attention in the last decades (Jueptner, Frith, Brooks, Frackowiak, & Passingham, 1997; Yan, 2017), learning of isometric force production of the hand is a scarcely investigated field in comparison (Godde, Trautmann, Erhard, & Voelcker-Rehage, 2018; Vieluf, Godde, Reuter, & Voelcker-Rehage, 2013). Up to date, there is a lack of both basic and applied research addressing the effect of different learning schedules on isometric force production of the hand.

The effect of variability of practice refers to a phenomenon whereby task variability during acquisition may reduce acquisition performance but facilitate learning as assessed by retention or transfer performance. Variability during motor learning has been applied as far as Bach's suits that are thought to have been teaching tools bringing gradually increasing variability into practice. But which one is more beneficial for retention and transfer of a skill learned on the instrument? Etudes by Popper that are close to blocked practice schedule? Or Bach who applies increasing variability during the learning of cello play? The effect of the variability in practice arised from Schmidt's schema theory (Schmidt, 1975). According to the schema theory, when an individual is practicing a movement, he or she develops motor response schemas, whereby new variations from the same general class of movement can be produced effectively. Many of the investigations which supported the above prediction of Schmidt's schema theory showed a common feature. That is, participants who practiced many variations of a motor task showed larger errors during acquisition as compared to those who practiced one variation. On the other hand, practice variability led to comparable or superior performance level when the learned tasks were produced either with the same conditions or with novel parameters (Schmidt & Lee, 2011).

The aim of the thesis was to investigate the effect of practice variability on isometric force production of the hand. First, two motor learning experiments (Experiment 1 and Experiment 2) were conducted in order to examine the effect of variability of practice itself, but a superior effect of variability of practice was not found in either of the two experiments using an isometric hand grip force production task. Because no beneficial influence of variability of practice was found, the question arised whether participants could differentiate between the force levels applied in Experiment 1 and Experiment 2. To examine this question a force discrimination experiment was administered in a subsequent study (Experiment 3). The aim of Experiment 3 was to find the discrimination threshold for an isometric hand grip force production task to be able to choose force levels below the threshold in later motor learning experiments making the motor learning tasks more difficult to acquire. Experiment 4 examined the variability of practice effect using below threshold inter-target differences. Experiment 5 aimed to find the effect of the range of applied parameters in variable schedule on learning. Experiment 6 was designed to reveal the effect of different practice schedules in regaining hand function after hemiparetic stroke, a frequent health condition.

Chapter 2 REVIEW OF LITERATURE

2.1 Hand movements

In the course of evolution, the development of hand function and tool invention and use generated each other and contributed to the development of human brain, language, cognition and culture (Almécija & Shwerwood, 2017; Jones & Lederman, 2006; Katona, 2014). The unique structure of the hand allows such a great number of postures and degrees of freedom during movements that is only present in humans but not in other primates (Xu et al., 2015). Fine motor control of the hand is the latest function we fully achieve during motor development (Payne & Isaacs, 2012). They develop until adulthood (Gervan, Soltesz, Filep, Berencsi, & Kovacs, 2017) and are subject to decline in older age (Jones & Lederman, 2006).

Studying hand function and fostering its development and learning is an important field in many aspects. In early childhood, appropriate hand functions form a basis for exploratory behaviour and cognitive development. They are necessary for discovering the characteristics of objects such as weight, surface or the perception of form (Jones & Piateski, 2006). Sensorimotor coupling between object characteristics (e.g., surface, weight) and motor demands forms a basis for skilful movement (Dafotakis, Grefkes, Wang, Fink, & Nowak, 2008; Wing, Haggard, & Flanagan, 1996).

Furthermore, hand function is inevitable for self-care, for activities of daily living and is in relation with the quality of life. It forms the basis for acquiring cultural techniques (e.g., writing). Children with higher level of fine motor skills experience higher level of scholarly competence (Piek, Baynam, & Barrett, 2006). The challenges of modern times in education, the use of digital technologies also assume appropriate fine motor function of the hand. Therefore, the examination of hand function, and the facilitation of its involvement in a broad range activities is an important task for somatopedagogy, an important field of special education. (Benczúr, 2000).

2.1.1 Characterization of hand movements

There have been many attempts to categorize the movements of the hand from different viewpoints (e.g., anatomical or biomechanical), but there is no agreement in a unified classification method up to date (Xu et al., 2015). Jones and Lederman (2006) proposed an integrated sensorimotor continuum for describing hand function (Figure 1.).

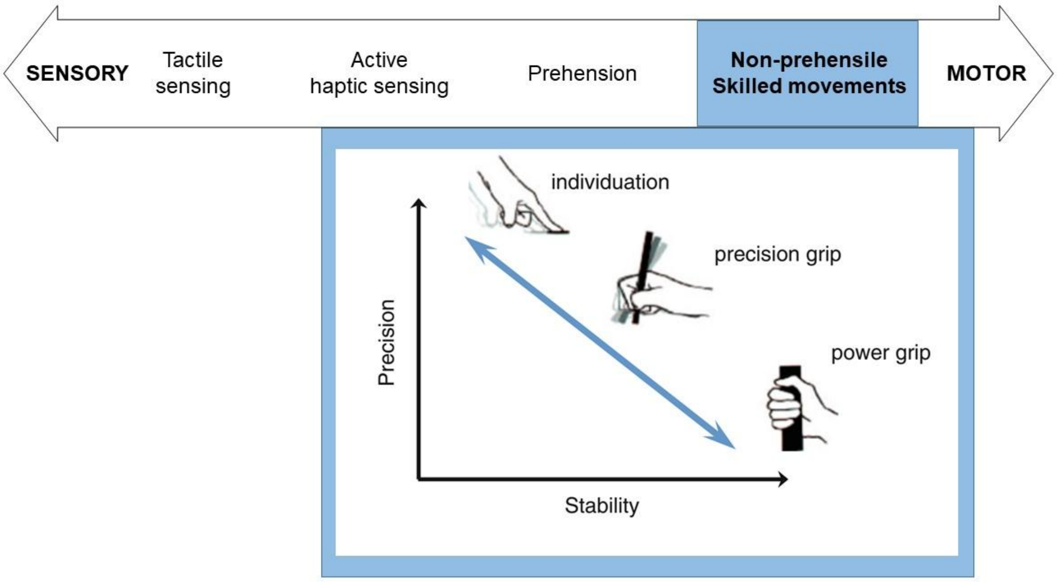

Figure 1. Classification of hand function on a sensorimotor continuum. Hand movements are classified as prehension (includes reaching) and non-prehensile skilful motions. Non-prehensile skilled movements can be further interpreted in a precision-stability coordinate system. Finger individuation allows precision while grip function allows stability for hand movements. Based on Jones and Ledermann (2006) and Xu et al. (2015).

On the sensory end, it starts from a passive hand function during tactile sensing when the object is either static or moving on the hand surface. Towards the motor function, it is followed by active haptic sensing where the hand has an active motor exploratory role in perception. Haptic perception has a goal of acquiring information about the objects with the hands such as shape, texture, weight (Bushnell & Boudreau, 1993). Prehension refers to hand movements involving grasping. It consists of three components of approaching, grasping and releasing objects (Payne & Isaacs, 2012). These movements usually require proprioceptive sensory input to perform precisely. In the categorization of Jones and Ledermann (2006), non-prehensile skilled movements represent the category requiring individuated finger movements.

Non-prehensile hand movements are commonly divided into precision and power grips (Napier, 1956). Recently, Xu et al. (2015) proposed a continuum that span non prehensile hand movements from power grip that ensures stability to finger individuation that represent maximal precision and flexibility. They placed precision grip midway between power grip and finger individuation since it requires both stability and precision (Figure 1.). Loss of individuation with increased force production can be seen as a transition from precision grip to power grip (Vaillancourt, Slifkin, & Newell, 2002). This phenomenon may also be present in cerebral palsy or after stroke as a part of the upper motor neuron syndrome (Xu et al., 2015).

Fine motor adjustments including adequate application of force are necessary in all types of active hand movements. Force control is defined “as a capability to generate accurate and steady force output that matches a target goal including timing and muscular force production” (Kang & Cauraugh, 2015). Application of static force, in other words isometric hand grip is a component ensuring stability during hand movements (Dafotakis et al., 2008; Johansson, 1996). While its role is emphasized more during power and precision grips (Dafotakis et al., 2008; Gilles & Wing, 2003), it may play a role also in individual finger movements such as in typing (Dennerlein, Mote, & Rempel, 1998) or playing a music instrument.

2.1.2 Control of hand grip

Isometric hand grip and individuated finger movements require a differential control and muscle activation (Xu et al., 2017). Neural structures involved in the learning of the two types of movement also show differences (Dayan & Cohen, 2011). Motor cortices of the cerebrum play a role in the preparation and set-out of voluntary movements (Lundy-Ekman, 2013). Activity in primary motor cortex is related to the magnitude of force production (Evarts, 1966, 1968), the perception of force (Slobounov, Hallett, & Newell, 2004) and the learning of isometric force production (Floyer-Lea & Matthews, 2005). These areas have direct connection to the spinal cord lower motoneurons through the lateral corticospinal tract allowing fast adjustments during voluntary actions (Lundy-Ekman, 2013). Both the cerebellum and the basal ganglia are involved in motor learning but weights in their contribution depend on the nature of the task. In tasks that require force adaptation cerebellum is involved in a greater extent after the cognitive phase of learning (Doyon & Benali, 2005; Shadmehr & Holcomb, 1997). Sensory contribution to hand function is studied since Mott and Sherrington in the 19^{th} century (Iwamura, 2003). Regarding force perception for motor control and learning, apart from the role of descending motor commands from the cortex (Jones, 1986; McCloskey, 1981) peripheral information from proprioceptors also plays an important role in controlling force output (Gandevia & McCloskey, 1978).

2.1.3 Effect of stroke on hand function

Stroke is defined as an „acute focal neurological dysfunction caused by focal infarction at single or multiple sites of the brain. Evidence of acute infarction may come either from a) symptom duration lasting more than 24 hours, or b) neuroimaging or other technique in the clinically relevant area of the brain" (Wold Health Organization, 2018). Stroke is a main cause of long term disability in adulthood (Langhorne, Bernhardt, & Kwakkel, 2011). Its symptoms and their severity depend on the affected brain site and the extensiveness of the lesion (Lundy-Ekman, 2013; Woodson, 2013). The most relevant activities affected are communicating and speaking; reading, writing, and calculating; solving problems; undertaking single and multiple tasks; transferring oneself; maintaining body position; walking; mobility; toileting; dressing; moving around, driving, and transportation; washing and self-care; hand and arm use; eating and drinking; use of transportation; recreation and leisure and doing housework (Langhorne et al., 2011). The limitation in these activities results in restriction in participation in numerous fields such as acquisition of goods and services, doing housework, basic interpersonal, recreation and leisure activities and remunerative employment (Langhorne et al., 2011).

The main causes of functional impairment are motor in nature (Langhorne et al., 2011). Motor symptoms include hemiparesis (80%), muscle weakness, impaired selective motor control, poor coordination and balance, altered reflex activity and muscle tone (Edmans, 2010; Szél, 2010; Woodson, 2013). Furthermore, not only the body side contralateral to the lesion, but also the ipsilateral side may be affected (Quaney, Perera, Maletsky, Luchies, & Nudo, 2005; Schaefer, Haaland, & Sainburg, 2009). In addition, sensory loss can also contribute to motor, especially hand dysfunction (Winward, Halligan, & Wade, 2007). 21-60% of stroke survivors are affected by sensory loss that is predominated by tactile and proprioceptive deficit (Connell, Lincoln, & Radford, 2008; Woodson, 2013). After stroke, impairment of arm and hand function is common (Franck, Smeets, & Seelen, 2017). Force control is characterized by decreased maximum force level, asymmetry between hands, higher error, and greater variability in force production (Kang & Cauraugh, 2015; Lindberg et al., 2012; Lodha, Patten, Coombes, & Cauraugh, 2012). Decreased grip strength and decreased dexterity with excessive force applied during hand-object interaction may be simultaneously present (Raghavan, 2007; Xu et al., 2015). Altered force control ability and decreased grip strength are directly related to the severity of functional impairment after stroke (Ding & Patten, 2018; Lindberg et al., 2012; Naik, Patten, Lodha, Coombes, & Cauraugh, 2011).

There is a considerable functional recovery within the first three months following stroke due to spontaneous recovery (Szél, 2010). In this acute phase, 87% of stroke survivors show paresis of the arm and hand (Knutson, Harley, Hisel, & Chae, 2007; Meng et al., 2017). Regaining hand function may be continued in rehabilitation programmes during the subacute phase (Franck et al., 2017). Level 1 evidence shows that involvement in rehabilitation programme during this phase improves functional outcome (Szél, 2017) but hand function may improve even twelve months after discharge (Franck et al., 2017). On the other hand, the majority of stroke survivors is not able to involve the hemiparetic upper extremity into activities of daily living twelve months after stroke (Woodson, 2013). Only approximately 12% of stroke survivors achieve complete functional recovery within 6 months (Kwakkel et al., 2017).

Methods for regaining hand and arm function are manifold and include bilateral training, constraint-induced movement therapy (Wu, Chuang, Lin, Chen, & Tsay, 2011), electrical stimulation (Wilson et al., 2016), virtual reality (Schuster-Amft et al.,

2018) high-intensity therapy (Knecht et al., 2016), motor imagery (Carrasco & Cantalapiedra, 2016), repetitive task training, robotics (Peter, Fazekas, Zsiga, & Denes, 2011), mirror therapy (Michielsen et al., 2011), and splinting or orthosis (Woodson, 2013). In contrast to the numerous beneficial or likely to be beneficial rehabilitation methods for lower extremity function, the number of evidence-based methods for hand function is lesser (Langhorne et al., 2011; Woldag & Hummelsheim, 2002). For example, electrical stimulation (Bolton, Caraugh & Hausenblas, 2004), constraint-induced movement therapy (Kwakkel et al., 2015) and non-immersive virtual reality training (Saposnik et al., 2016) are proved to be beneficial for upper extremity rehabilitation after stroke. Regaining hand function is a crucial field of rehabilitation after stroke since it has an inevitable role in daily living activities, in social participation and therefore affects the quality of life (Hőgye, Jenei, & Vekerdy-Nagy, 2016). Therefore, the exploration of effective motor training methods for hand function after stroke is an ongoing process that urges the innovation and examination of novel methods to the field.

2.2 Motor learning

2.2.1 Definitions

Motor learning or motor memory formation is defined as an improvement of a motor skill through practice or experience that is associated with long-lasting neuronal changes (Brem, Ran, & Pascual-Leone, 2013). On the behavioural level, the course of motor learning is characterized by an initial phase called fast learning referring to the marked improvement in performance in this stage (Anderson, 2000; Dayan & Cohen, 2011). This phase is also characterized by understanding the task and performance criterion, high attentional demands, and increased role of feedback techniques. This phase is followed by a slow learning phase where improvement is decreased after the same amount of practice, and performance requires less attention when it becomes automatic (Anderson, 2000; Dayan & Cohen, 2011). Conceptual frameworks explaining memory formation mechanisms behind the performance changes emerged from the early 1970s (Adams, 1971a) and still formulated nowadays (Debas et al., 2010) by the development of methodology and functional imaging techniques. Two influential frameworks that have their impact up to date were Adams' closed-loop theory and, as a response to that, Schmidt's schema theory (1975).

2.2.2 Adams' closed-loop theory

Adams' closed-loop theory of motor learning (Adams, 1971) proposed that there are two states of memory, called the memory trace and the perceptual trace. The memory trace is responsible for initiating the movement, choosing the initial direction of the movement, and determining the earliest portions of the movement. Adams emphasized that the strength of the memory trace is developed as a function of knowledge of results (KR) and practice. While the role of the memory trace is to initiate the movement, the role of the perceptual trace is to guide the movement. The perceptual trace is formed from the past experience with feedback from earlier responses and represents the sensory consequences of the movement. During the movement, the performer compares the incoming feedback against the perceptual trace to determine whether the movement is correct. In the case of a correct movement the performer stops responding, but if there is a difference between the actual movement result and the perceptual trace, the performer makes an adjustment and the comparison is made again until the movement is correct. With increased feedback information, the perceptual trace is strengthened, and the individual becomes more accurate and confident in his responding. Therefore, according to Adams, closed-loop theory sensory information, or response produced feedback during and after the movement, is a crucial source of information to affect motor learning.

2.2.3 Schmidt's schema theory

In Adams' theory some questions remained unanswered. One question was the novelty problem of learning, that is, how an individual learns a motor task he or she never performed previously. Moreover, Adams emphasized the primary importance of the response produced sensory feedback for motor learning. However, there are rapid movements in which there is no time for processing such feedback information. Furthermore, in Adams' theory the storage problem of the memory of individual movements remained unanswered.

To resolve this discrepancy (Schmidt, 1975) proposed that rapid movements are produced by using generalized motor programs and schemas, with which generalized motor programs can be scaled to produce adequate motor responses sufficient for the originally intended movement goal.

The schema (an organized structure of knowledge) is a set of relationships among four kinds of information related to the movement, initial conditions, response specifications, sensory consequences, the outcomes of the response. The schema is not a specific motor program, but is a guide or general set of rules of how to perform a certain class of movements. A class of movements refers to any motor behaviour that share the same invariant features such as relative timing, phasing, relative force, or in other words movements that have the same structure.

According to the schema theory, when an individual is practicing a movement, he or she develops two kinds of motor response schemas, whereby new variations from the same general class of movement can be produced effectively. One of the motor schemas developed by practice, termed the recall memory, is the motor program itself, a pre-packaged sequence of actions. The recall schema links movement outcomes to certain movement parameters, such as force and movement duration, considering initial conditions. Recall schemas are responsible for response production. The second kind of motor response schema, called the recognition schema, is a representation of the desired outcome of the action in terms of both the response-produced feedback and the external sensory consequences. The recognition schema links movement outcomes to sensory consequences, taking initial conditions into account. The recognition schema concerns response evaluation.

Therefore, one of the original thoughts of the schema theory was that motor programs are generalized, and can be executed in many different ways by scaling them with different parameters by using the above-mentioned motor response schemas.

The schema theory also predicted that increasing the variability in the practice of a given movement class will enhance the development of the motor response schema resulting in better performance in transfer and retention. This prediction was termed the variability of practice hypothesis (Moxley, 1979).

2.2.4 Bayesian model in motor learning

While not in the focus of the present thesis, models of statistical inference that have given new insights into motor control and learning in the last decades should be also mentioned. These models focus on how previous experience teaches us to predict future events (Neal, 1995). In the field of motor control, a relatively well studied model comes from the Bayesian theory (Berniker and Kording, 2011). In establishing relationship between sensory and motor parameters for motor planning, Bayesian inference uses prior knowledge for the estimation of the likelihood of each possible outcome (Russel and Norvig, 2005). That is not only the most likely outcome is computed and concerned. Following the movement, the estimates of the a priori probabilities are updated in the model for future actions. For example, applied force will be adjusted based on prior experiences on object size, shape, and texture during lifting movement.

This framework has been studied in relation of various types of movement such as reaching movements, postural control, and sensory weighting from visual and proprioceptive sources as well as force estimation (Körding et al., 2004). Furthermore, a priori experiences influence motor planning in terms of errors as well but motor planning is based not only on the magnitude of previously committed errors. Adaptation of movement trajectories are also based on the relevance of error during a given type of movement (Wolpert, 2009). In the field of motor learning, the relationship with neither the Adam's nor the Shmidt's model has been approached up to date.

2.2.5 Variability of practice research

2.2.5.1 Variability of practice research in typical development

The variability of practice hypothesis was examined in several previous studies using sequential timing tasks (Giuffrida, Shea, & Fairbrother, 2002; Hall & Magill, 1995; Lai, Shea, Wulf, & Wright, 2000; Lee, Magill, & Weeks, 1985; Proteau, Blandin, Alain, & Dorion, 1994; Shea, Lai, Wright, Immink, & Black, 2001; Wulf & Schmidt, 1988), aiming tasks (Goodwin, Grimes, Eckerson, & Gordon, 1998; Moxley, 1979; Sherwood, 1996), and sport related tasks (Douvis, 2005) over the last decades.

It has been shown that the effect of variability of practice is a function of the order, with which the tasks follow each other during the acquisition phase. The schedule of the tasks is an important factor which influences motor learning. As (Lee, Magill, &

Weeks, 1985) demonstrated, random-scheduled variable practice is more effective for learning than a blocked-scheduled practice. In a blocked practice schedule, the learner practices multiple variations of a skill, but each variation is practiced for a given period of time before the next variation is introduced. For example if there are 3 task variations to be practiced, called Task A, Task B, and Task C, a blocked order of task variations can be: AAA...BBB...CCC. Conversely, practicing in a random practice schedule requires that the learner practices each of the skill variations in a random order. Learning was more effective after random practice as opposed to blocked practice in several investigations (e.g., Sherwood, 1996; Proteau et al., 1994; Shea & Kohl, 1990), supporting the variability of practice hypothesis for motor learning.

There are factors other than schedule that can influence motor learning. The way of providing feedback during acquisition has an effect on motor learning. It has been shown that augmented feedback, where feedback is provided after every trial, not necessarily leads to superior performance in comparison with summary feedback where feedback is provided summarized after a block of trials (Gable, Shea, & Wright, 1991; Sidaway, Moore, & Schoenfelder-Zohdi, 1991). Another important factor affecting motor learning is the amount of practice. (Shea, Kohl, & Indermill, 1990) have found that the beneficial effect of the variable practice improved as the number of acquisition trials increased.

A phenomenon of deep interest has emerged in the course of variability of practice research. In a series of experiments of Shea and Kohl (1990, 1991) the participants learned to exert an isometric, impulsive contraction at a desired force with their lower arm. During the acquisition phase the performance of participants practicing only one force level at the criterion task (constant group) was superior to the performance of participants practicing not only the criterion task but also the variations of it (variable group). However, when learning effect was tested, in spite of its inferior performance during acquisition, the variable group showed superior performance in comparison with the constant group. This phenomenon was found in other studies too (e.g., Lai & Shea, 1998; Lai et al., 2000; Lee et al., 1985; Proteau et al., 1994; Sekiya, Magill, Sidaway, & Anderson, 1994; Sherwood, 1996).

2.2.5.2 Schmidt's schema theory 40 years on

Examining the effect of variable practice forty years after the emergence of the schema theory (1975) is still current. In recent years, Travlos and colleagues (2010) reported that greater variability results in decreased performance when learning volleyball serve. Furthermore, there was a similar learning effect after constant and variable practice in a functional force production task (Marchand, Mendoza, Dugas, Descarreaux, & Page, 2017), and during speech learning in simple and complex tasks (Kaipa, 2016). On the other hand, Czyz and Moss (2016) found a beneficial effect of practicing with four different parameters in archery. They showed that performance was improved not only with the practiced parameters but also within the range of practiced parameters. It suggested the formation of a schema being beneficial for transfer processes and promoting performance improvement within a range of parameters.

While predictions of the schema theory are based primarily on discrete movements (see above), its examination has been extended to the field of continuous movements as well. Regarding postural control, increased variability during practice resulted in decreased performance during acquisition but in superior post-training performance in an asymmetric gait task (Hinkel-Lipsker & Hahn, 2017).

The study of other task aspects, such as the use of feedback or the level of proficiency, have been also included into the variability of practice research.

Introducing variability into the training program promotes the utilization of online kinaesthetic information (Tremblay, Welsh, & Elliott, 2001). The importance of processing proprioceptive feedback is showed by a study where actual motor execution and variability in practice resulted in learning effect while introducing variability in mental training did not (Coelho, Nusbaum, Rosenbaum, & Fenn, 2012). Furthermore, Taheri, Fazeli, and Poureghbali (2017) showed that the effect of practice variability may depend on the level of proficiency in the learned task. While the performance of beginners may deteriorate by increased variability, the performance of skilled players did not show such an effect.

From a developmental perspective, it has been hypothesized that children have less motor experience than adults thus variable practice should be more effective (Shapiro and Schmidt, 1982). It has been supported by the findings of Kerr and Booth (1977, 1978) in throwing skills and that of Green, Whitehead and Sudgen (1995) in racket skills. On the other hand, Pease and Rupnov (1983) found no beneficial effect of practice variability when children needed to adapt to different force levels when moving along a toy car on a track. Recent literature emphasizes the importance of variability during motor learning (Hadders-Algra, 2010) and may have a role in the development cognitive domain as well (Pesce, Croce, Ben-Soussan, Vazou, McCullick, Tomporowski, & Horvat, 2019)

2.2.5.3 Variability of practice in atypical development and after central nervous system damage

The schema theory appears as a feasible framework also in the field of motor rehabilitation (Morris, Summers, Matyas, & Iansek, 1994), nonetheless, its systematic investigation has not taken place up to date.

During learning wheelchair use, variable practice was more beneficial than constant practice for learning speed adaptation when learners were healthy young adults (Yao, Cordova, De Sola, Hart, & Yan, 2012). After stroke, upper extremity training using random and block variable schedules were more effective when accompanied with functional electrical stimulation than in its absence (Cauraugh & Kim, 2003). No differential effect was found, however, after a one-session gait training according to variable and constant schedules (Rhea, Wutzke, & Lewek, 2012). In the elderly and in Alzheimer-disease, the presence of practice variability shows a differential effect in the two populations. In the healthy elderly population, there was no difference between the effects of constant, block and random practice in a throwing task. In Alzheimer-disease, constant practice resulted in retention and transfer of the learned task, but variable schedules of block and random practice did not (Dick, Hsieh, Dick-Muehlke, Davis, & Cotman, 2000). In specific language disorder, variability of practice supported task generalization when learning a spatially demanding upper extremity task (Desmottes, Maillart, & Meulemans, 2017). However, the variable schedule resulted in similar effect as the constant schedule during phonation practice (Wong, Ma, & Yiu, 2011).

Notwithstanding the contradictory results regarding the superior effect of practice variability, the majority of the above studies show that introducing variability during acquisition of a skill does not result in a detrimental learning effect. On the contrary, a huge body of studies supports that despite decreased performance during acquisition, practice variability may be beneficial for learning.

Chapter 3 ISSUES TO BE INVESTIGATED AND METHODS IN THIS STUDY

3.1 AIMS AND RATIONALE

3.1.1 Overall aim and rationale

The aim of the present study is to examine the characteristics and effects of variable practice schedule in contrast to constant practice schedule in learning hand movements. Isometric force production is an inevitable but scarcely studied component of hand function. The focus of the present thesis is to reveal if specific traits of variable practice such as higher level of errors during practice, effective retention, and superior transfer performance compared to constant practice are present when learning appropriate isometric hand grip.

3.1.2 Experiments 1 and 2.

Experiments 1 and 2 were the adaptations and re-examinations of the variability of practice effects found by Shea and Kohl (1990, 1991) in an isometric force production task. My hypothesis was that specific features of variable practice conditions would be present in the case of learning an isometric hand grip force production task. First, variable practice schedule will result in decreased performance during the acquisition session. Second, it will result in comparable level of skill retention and comparable or higher level of transfer performance when compared to constant practice schedule.

3.1.3 Experiment 3.

Experiment 3 aimed at characterizing the discrimination threshold level for isometric force production task. My hypothesis was that the discrimination threshold for isometric force production would be similar or higher than in isotonic force production tasks.

3.1.4 Experiment 4.

In Experiment 4, I planned to examine the effect of variability of practice using an isometric hand grip force production task with force level differences below the discrimination threshold gained in Experiment 3. My hypothesis was that increasing difficulty in the means of decreased inter-target difference but keeping the number of task variations invariable may result in improved performance in terms of retention and transfer in the variable practice group.

3.1.5 Experiment 5.

In Experiment 5, the goal was to examine the effect of varying intertarget difference and range of parameters on acquisition performance, retention and transfer. My hypothesis was that if the schema theory holds, increased variability with a broader range of force production levels experienced in practice would be advantageous in subsequent retention and transfer tests.

3.1.6 Experiment 6.

The aim of the study was to determine the characteristics and the effects of variable vs. constant practice on the learning process of isometric hand grip force production by the hemiparetic hand following unilateral stroke. My hypothesis was that the characteristics of variable practice as compared to constant practice e.g., higher error level during practice but successful or more effective learning in terms of retention and transfer would be present after hemiparetic stroke.

3.2. GENERAL METHODS AND DATA ANALYSIS

3.2.1 Participants

In experiments 1-5, participants were healthy university students from Tokyo Metropolitan University (Table 1.). Their age range was 18-29 years and they had no musculoskeletal or neurological disorders. All participants were right handed.

Participation in the studies was voluntary and subjects received course credit for participation. Informed consent was obtained from all participants. Studies were conducted according to the Declaration of Helsinki 5th revision.

		males	females	mean age (years)	age SD (years)
Experiment 1	constant group	4	0	25.8	3.2
	variable group	4	0	28.4	3.2
Experiment 2	constant group	14	1	19.8	.6
	variable group	13	2	20.1	.8
Experiment 3		4	5	24.3	2.4
Experiment 4	constant group	6	2	25.1	4.1
	variable group	5	3	24.2	2.7
Experiment 5	constant group	6	2	20.2	1.3
	variable 2.5% group	6	2	19.8	.9
	variable 5% group	6	2	21.8	4.1
	variable 10% group	6	2	21	2.4

Table 1. Participants of Typical development in Experiments 1-5.

In experiment 6, participants were hemiparetic stroke patients, all inpatients at the National Institute for Medical Rehabilitation, Budapest. They did not have prior experience with the experimental task. All participants were informed of the experimental procedures in advance and provided informed consent for participating in the experiments. Detailed information on participants in Experiment 6 is in Table 4. on page 72.

3.2.2 Apparatus

The apparatus used in experiments 1-5 consisted of an isometric hand grip dynamometer (Takei, T.K.K. 5710) connected to a data acquisition box (National Instruments BNC 2120), which was connected to a personal computer (PC, Power Macintosh 8500/150). In experiment 6, the force measurement was performed by the Alladin Diagnostic Device. Here, JR3 force sensors (multi-axis load cells) measuring force exertion of the thumb, index and middle fingers were applied (Mazzoleni et al., 2012). The sensors were connected to a PC running the LabVIEW systems engineering software.

The LabVIEW 5.0 (Experiments 1-5) and LabVIEW 8.5 (Experiment 6) softwares run on the computers were programmed by the author to read and store force data. The same programme was used for data processing (e.g., calculation of errors) and the visual display function was used to provide information for the participants about task requirements and feedback on actual performance.

Apart from the experimenter's monitor that was used for controlling the LabVIEW software, a second monitor was connected to the PC in order to provide target forces and feedback to subjects about the magnitude of force produced by the participants (Fig. 2). Visual display for target forces and feedback have been previously approved in force production tasks both in healthy participants and those with disability (Jones, 2000; Kahn, Rymer, & Reinkensmeyer, 2004; Shea & Kohl, 1990).

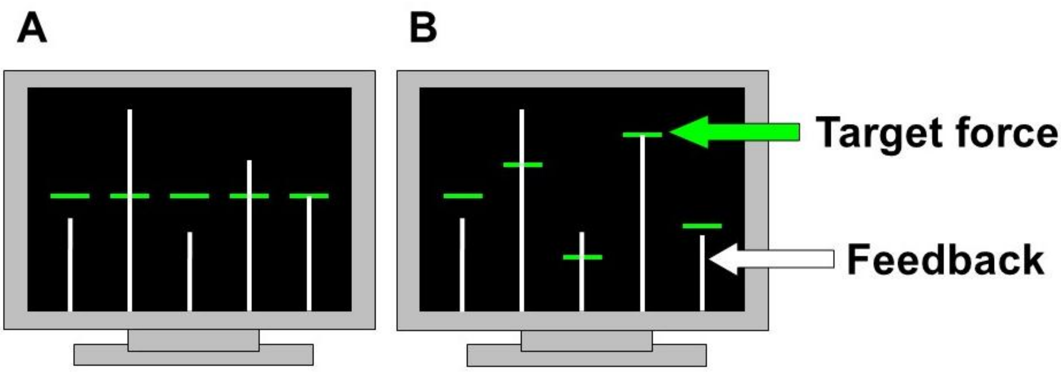

Figure 2. Visual display provided for participants under constant practice conditions (A) and variable practice conditions (B) in motor learning experiments. Green lines represent target forces and white lines represent feedback on the actual performance, respectively.

3.2.3 Procedure

3.2.3.1 Positioning

Participants were asked to sit comfortably in a chair in front of a table. The computer monitor was situated so that the monitor screen was in plain view. The lower arm was supported and the isometric hand grip dynamometer/force sensor was positioned so that participants could comfortably grip it with the right hand or hemiparetic stroke patients with the affected hand, respectively.

3.2.3.2 Maximum force measurement

In order to adapt target forces to individual performance, each experiment started with the measurement of maximum voluntary contractions (MVC). Here, participants were asked to exert a force as great as possible for four seconds by the right hand/affected hand. It was recorded three times with self-paced rests between the trials. Maximum force was defined as the average of peak force of the three trials.

3.2.3.3 Motor learning experiments

In motor learning experiments the display shown in Figure 3. was presented to the participants. Target forces were represented by green lines that appeared one by one on the black screen. After the first target force level appeared, participants were asked to exert hand grip within 1s while adjusting the force level to the height of the green line. The higher the green line appeared the higher the exerted force level should have been. 3s after force exertion, a white bar appeared the height of which indicated the actual level of force exerted. The next target force followed the feedback by 3s. Five trials were a sub-block, after that the screen cleared. A block consisted of four sub-blocks (20 trials). After each block a self-paced rest was administered. Before the learning session participants were allowed to familiarize with the procedure of the task (i.e., target line, feedback) without any actual force production.

Acquisition consisted of 16 blocks. Participants under constant practice conditions practiced only the target force. Participants under variable practice conditions practiced the target force and other four force levels (exact values were indicated at each experiment). The amount of practice was the same in both practice conditions.

Twenty-four hours after the acquisition session, both the retention and transfer tests were administered. In the retention test participants were required to produce trials of the criterion force production. The transfer test consisted of a novel force level which was not experienced during the acquisition session.

3.2.4 Measurement of dependent variables in motor learning experiments

Errors are common measures for monitoring changes in performance during the learning process (Schmidt & Lee, 2011). There are several types of errors for monitoring different aspects of performance (Rose, 1997). The following types of errors were used in experiments included in the dissertation:

3.2.4.1 Absolute error

Absolute error (AE) shows the absolute difference between the force level exerted by the participant and the target force. AE does not consider direction of the error (overshoot or undershoot), therefore eliminates error caused by bidirectional values at summation. It is calculated as $Error_{absolute} = \Sigma|x_i - T|/N$, where x is the actual force produced, T is the target force level and N is the number of trials (Schmidt & Lee, 2011). AE is used for indicating the overall accuracy in performance.

3.2.4.2 Constant error

Constant error (CE) shows the magnitude and direction of the difference between the target force and the force produced by the participant (overshoot or undershoot). It is calculated as $Error_{constant} = \Sigma(x_i - T)/N$, where T is the target force level, x_i is the actual force production and N is the number of trials (Schmidt & Lee, 2011; Shea, Shebilske, & Worchel, 1993). Bidirectional values of errors are eliminated in CE.

3.2.4.3 Variable error

Variability in motor performance is often applied to measure skilled performance (K. M. Newell & Corcos, 1993). Variable error (VE) shows the standard deviation of constant error, that is deviation from the performer’s own average. It is calculated as

VE = $\sqrt{\sum(x_i\text{-}M)^2 / n}$, where M is the average force exertion, x_i is the actual force production and n is the number of trials (Schmidt & Lee, 2011). A lower level of within subject variability is related to a more skilled performance.

3.2.4.4 Total error

Total error (E), also referred to as root means square error or total variability, indicates both deviation from target and consistency of performance. It is calculated as E = $\sqrt{\sum(x_i\text{-}T)^2 / n}$ where T is the target force level, x_i is the actual force production and N is the number of trials (Schmidt, Lee, Winstein, Wulf, & Zelaznik, 2019). It is often referred to as the best to capture both bias relative to the target and performance variability in a single measure (Rose, 1997).

3.2.5 Learning curve

On the behavioural level, the course of motor learning can be examined by the means of learning curves. Learning curves plot performance in the function of practice or time (Anderson, 2000). The learning function follows a power law (Newell & Rosenbloom, 1981), that is, performance gains are greater at the beginning but gradually decrease with practice. In the present experiments, AE, VE, CE and E were represented as a function of practice. Analysis of learning curves included the comparison of initial performance at the beginning of practice (1st block), the block-to-block changes during acquisition and the performance of the last practice block (Figure 3.).

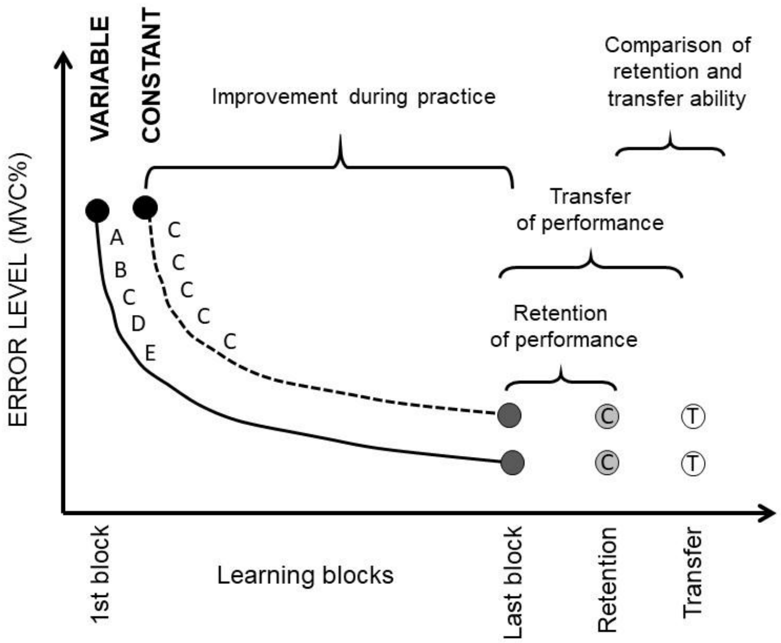

Figure 3. A schematic diagram of the points of analysis of the learning curves, retention and transfer tests in the present study. A block-to-block analysis of learning performance, comparison between the first and last block of acquisition performance (improvement during practice; black-dark grey dots), retention of acquired performance by the end of the practice (dark-light grey dots), transfer of the acquired performance to a novel parameter (dark grey-blank dots) and difference between retention and transfer performance (light grey-blank dots) were analysed within the group by repeated measures design. A between group comparison of the indicated points was also performed between the constant group (practicing the criterion task, C) and the variable group (practicing 5 parameter variations, A, B, C, D, E).

3.2.6 Retention

Retention refers to the persistence of the performance following practice (Schmidt & Lee, 1999). The retention test was performed under the same conditions as the acquisition session but without providing feedback. The target force was the same as practiced during acquisition. Performance mean in the blocks of retention tests, initial performance in the retention test, trial-to-trial improvement, and difference scores between retention test performance and that of the last block of acquisition were analysed.

3.2.7 Transfer

The transfer test was performed under the same conditions as the acquisition session, with the exception that the target force was a novel parameter variation. Performance mean in the blocks of transfer tests, initial performance in the transfer test, trial-to-trial improvement, and difference scores between transfer test performance and that of the last block of acquisition were analysed.

3.2.8 Statistical analyses

A two-way multivariate ANOVA for the two groups (constant and variable) × practice blocks/retention/transfer with repeated measures on practice blocks/retention/transfer was performed on error data. If significant interaction appeared, either a simple interaction test (for second order interaction) or a simple main effect test (for the first order interaction) was administered. Post hoc multiple comparisons analysis was performed by Least Significant Difference (LSD) test. A p-value of 0.05 was set as significance level at each test.

Chapter 4. EXPERIMENTS

4.1 Experiment 1 and Experiment 2. The effect of variable practice on the acquisition of an isometric hand grip force production task

4.1.1 Introduction

Two experiments were conducted to study the effect of variability of practice on acquisition performance, retention and transfer characteristics when learning a force production task by the hand. In both experiments, a part of the subjects were required to practice only a criterion task during an acquisition session, while the others practiced both the criterion task, and variations of it. The experiments were motivated by the study by Shea and Kohl (1990) who found a beneficial effect of variable practice on isometric force production when learning a gross motor task of elbow extension. Therefore, Experiment 1 and Experiment 2 were the re-examinations of the original Shea and Kohl study (1990) adapted for isometric grip force production. In the second experiment, feedback conditions changed from summary feedback to augmented feedback, and the number of trials of retention and transfer were increased. The aim of the experiments was to investigate if the same patterns of performance characterize the acquisition and retention of hand movements as found by Shea and Kohl (1990). My hypothesis was that the performance in hand grip force production follows the previously seen pattern: higher level of errors during acquisition but comparable or superior performance in retention and transfer tests under variable practice conditions compared to constant practice conditions.

4.1.2 Experiment 1

4.1.2.1 Method

4.1.2.1.1 Participants

Eight undergraduate university students participated in Experiment 1. Four males practiced under constant, and 4 males under variable condition. Mean age was 27.1 years (*SD* = 3.3 years).

4.1.2.1.2 Procedure

Following maximum force measurement, participants were assigned into two practice groups, the constant and variable groups for acquisition sessions. In the constant group, participants practiced only one force level, which was the exertion of 25% of their MVC, called a criterion task. In the variable group, participants practiced not only the criterion task, but also four variations of it, namely 15, 20, 25, 30, and 35% of their MVC in a randomized order. In the acquisition session of the present experiment both the constant and variable group practiced a total number 336 trials. The 336 trials were divided into 16 blocks of 21 trials, with each block of 21 trials being further divided into 4 sub-blocks. Participants received summary feedback at the end of each sub-block. Participants were required to exert a specified force with a fast grip movement and then to leave the handle of the dynamometer.

Twenty-four hours after the acquisition session, a retention test and a transfer test were conducted. In the retention test participants were required to produce 5 trials of the criterion task (i.e., 25% MVC). The transfer test consisted of 5 trials of a novel task, which was not practiced during the acquisition, namely 40% of the MVC. The inter-trial interval in the retention and transfer tests was identical with that used in the acquisition.

4.1.2.1.3 The dependent variables

The dependent variables were AE, CE and VE expressed in each participants own MVC%.

4.1.2.1.4 Statistical analyses

Statistical analyses were performed separately for acquisition (Blocks 1-16), retention (5 trials), and transfer (5 trials) on each type of error data. A two-way ANOVA (2 groups, 16 blocks) was performed for acquisition and a two-way ANOVA (2 groups, 5 trials) for each retention and transfer.

4.1.2.2 Results

4.1.2.2.1 Absolute error

Mean absolute errors are plotted on Figure 4. A two-way ANOVA (2 groups, 16 blocks) performed on acquisition showed that the main effects for both group ($F_{1, 6}$=7.18, p<.05) and block ($F_{17, 102}$=5.38, p<.01) were significant. The variable group produced significantly greater errors than the constant group. A subsequent multiple comparison test revealed that the first block of trials showed significantly greater errors ($F_{17, 102}$=5.38, p<.01) than those in all other blocks. In the retention and transfer tests, no main effect for either group or block was found.

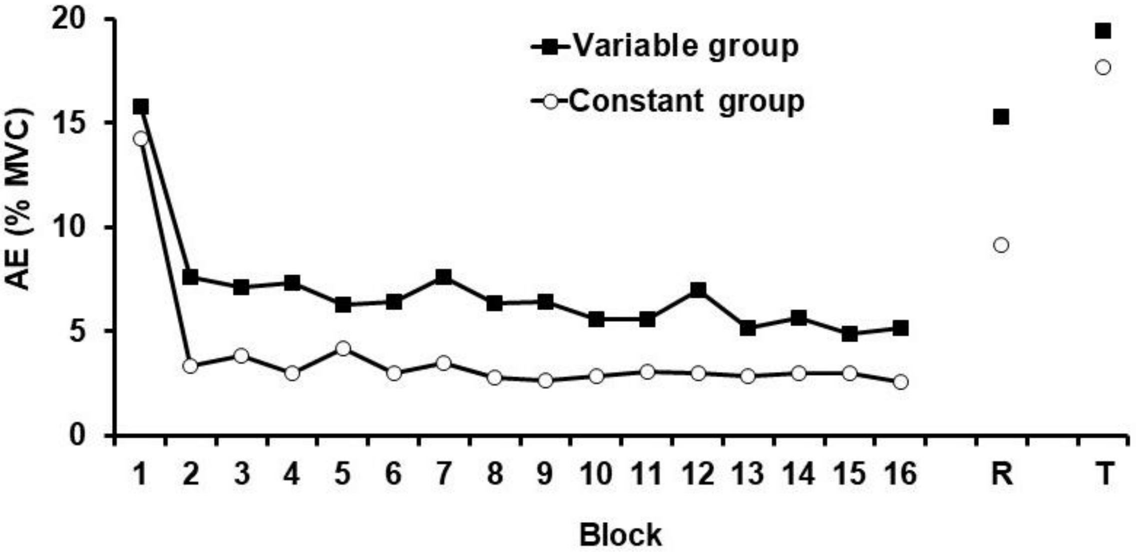

Figure 4. The mean absolute error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

4.1.2.2.2 Constant error

A two-way ANOVA (2 groups, 16 blocks) was performed on constant error data on acquisition. The mean constant errors are plotted on Figure 5. No significant main effect for group was found in the acquisition session ($F_{1, 6}$=1.41, p>.05). The analysis indicated a significant main effect for blocks ($F_{17, 102}$=2.46, p<.01). Subsequent multiple comparison tests on acquisition blocks indicated that the first block was different than all other blocks. In the retention and transfer tests, no main effect for either group or block was found.

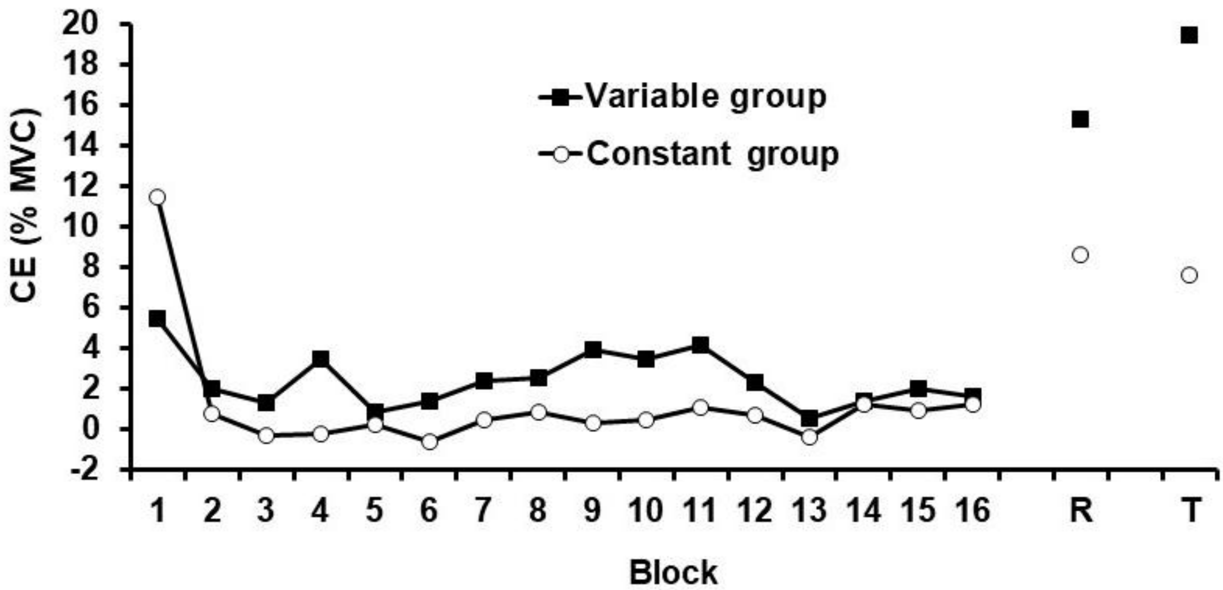

Figure 5. The mean constant error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

4.1.2.2.3 Variable error

The mean variable errors are plotted on Figure 6. A two-way ANOVA (2 groups, 16 blocks) performed on acquisition showed that the main effects for both group ($F_{1, 6}$=10.20, $p<.05$) and block ($F_{17, 102}$=7.04, $p<.01$) were significant. The variable group produced significantly greater errors than the constant group. Subsequent multiple comparison tests revealed that the first block of trials showed significantly greater errors than those in all other blocks ($p<.05$). In the retention and transfer tests, no main effect for either group or block was found.

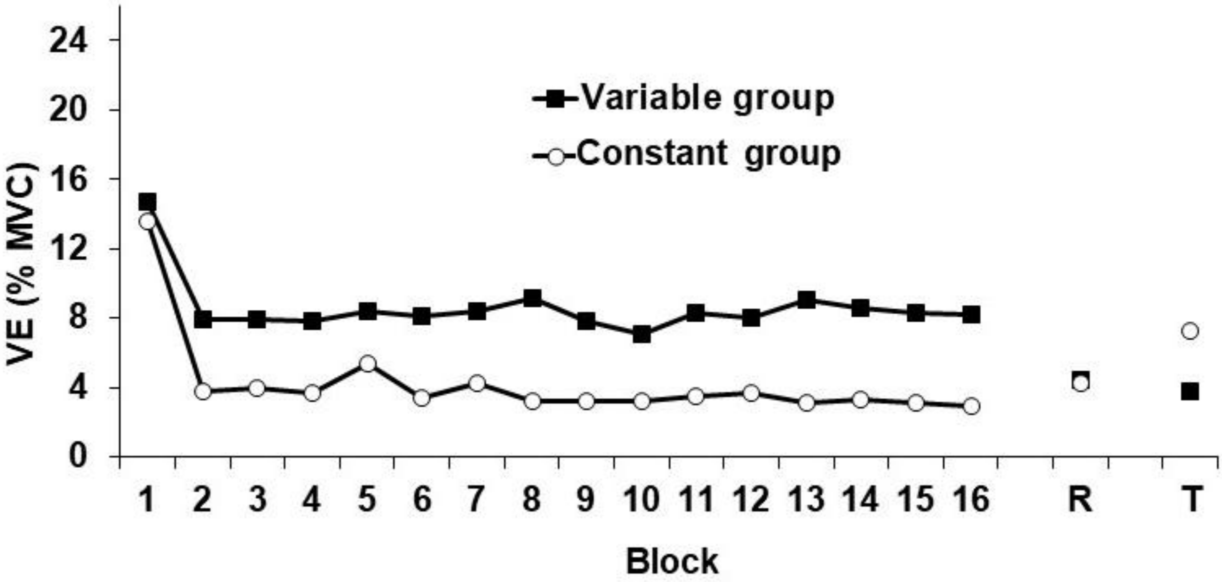

Figure 6. The mean variable error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

In summary, results of Experiment 1 showed significant difference between variable and constant practice schedule during acquisition. Variable practice schedule resulted in significantly higher error level in terms of magnitude of error indicated by AE and consistency of performance (VE). On the other hand, difference in practice schedule did not result in significantly different retention and transfer performance of the two groups.

4.1.3 Experiment 2

4.1.3.1 Method

4.1.3.1.1 Participants

Thirty undergraduate students (27 males and 3 females) participated in the experiment. Mean age was 19.5 years (*SD*= .7 years). Participants were randomly assigned into one of the two practice groups, the constant group and the variable group.

4.1.3.1.2 Apparatus

The apparatus was the same as in Experiment 1.

4.1.3.1.3 Procedure

The procedure was identical to Experiment 1 with the following expectations:
In Experiment 2, the participants received augmented feedback after each force production during acquisition. The inter-trial interval was 4s. In the retention test, participants were required to produce 12 trials of the criterion task (i.e., 25% MVC). The transfer test consisted of 12 trials of a novel task, which was not practiced during the acquisition, namely 40% of the MVC. The inter-trial interval in the retention and transfer tests was 36s. Augmented feedback information after every force production was displayed on the computer monitor during both retention and transfer tests.

4.1.3.1.4 The dependent variables

The dependent variables were AE, CE, and VE.

4.1.3.1.5 Statistical analyses

Statistical analyses were performed separately for acquisition (Blocks 1-16), retention (12 trials), and transfer (12 trials) on each type of error data. A two-way ANOVA (2 groups, 16 blocks) was performed for acquisition and a two-way ANOVA (2 groups, 12 trials) for each retention and transfer. A 2 × 3 (variable/constant groups x last acquisition block/retention/transfer) ANOVA was further performed on each type of error data.

4.1.3.2 Results

4.1.3.2.1 Absolute error

Mean AEs are plotted on Figure 7. A two-way ANOVA (2 groups, 16 blocks) performed on acquisition showed that the main effects for both group ($F_{1, 28}$=57.53, p<.01) and block ($F_{15, 420}$=22.4, p<.01) were significant. The variable group produced significantly greater errors than the constant group. Subsequent multiple comparison tests revealed that the first block of trials showed significantly greater errors ($F_{15, 420}$=22.4, p<.01) than those in all other blocks.

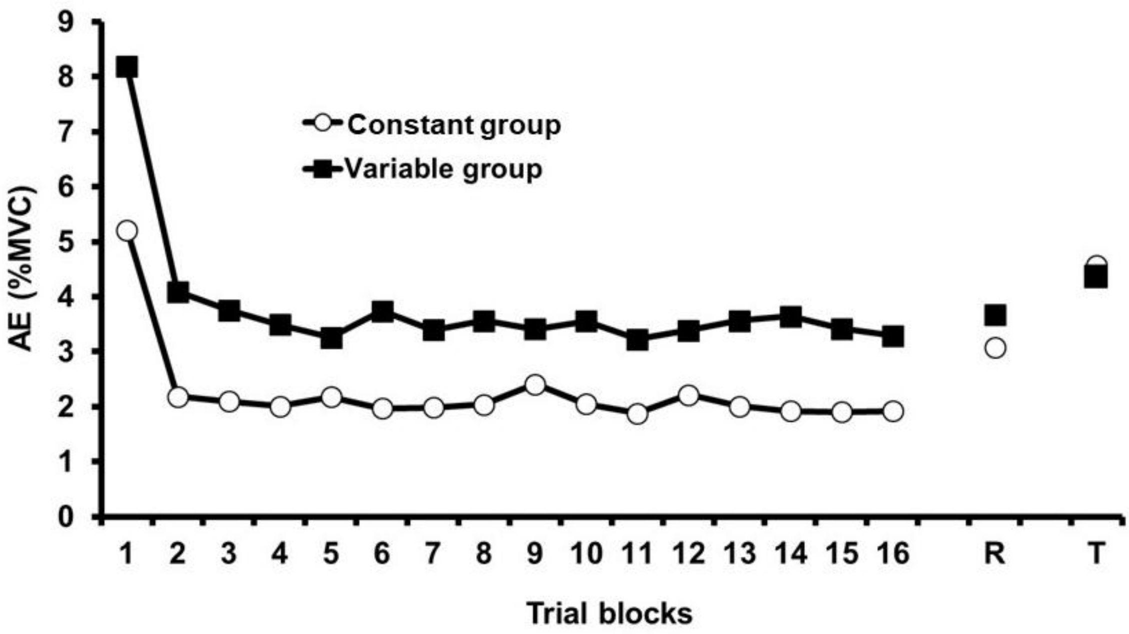

Figure 7. The mean absolute error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

A two-way ANOVA (2 groups, 12 trials) was performed for the retention test (Figure 8.). No significant main effect for group was found ($F_{1, 28}$=1.67, p>.05). There was a significant main effect for trials ($F_{11, 308}$=12.37, p<.01). Subsequent multiple comparison tests on retention trials showed that the first trial differed from all other trials, values being significantly higher in both groups.

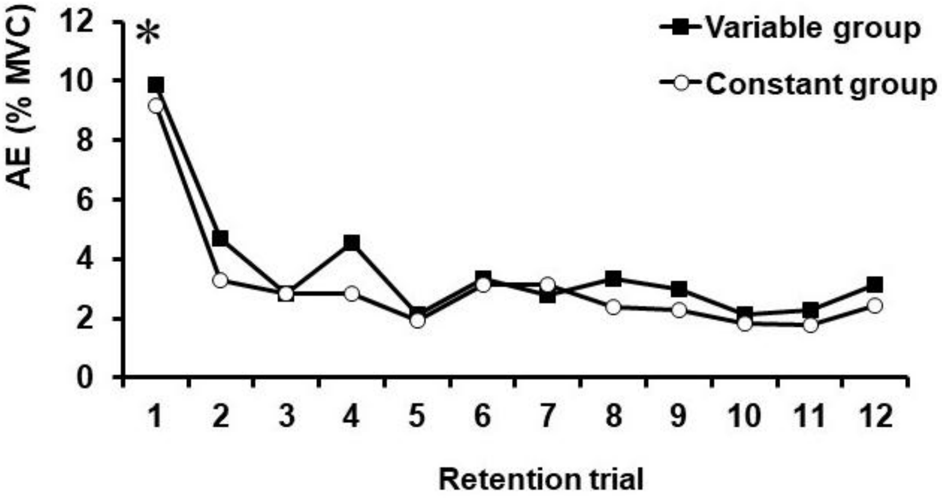

Figure 8. Trial-by-trial mean absolute error in retention test. The vertical axis shows the errors in % of MVC.

A two-way ANOVA (2 groups, 12 trials) was performed for the transfer test. In the transfer test, there was no significant main effect for either group ($F_{1, 28}$=0.32, p>.05) or trials ($F_{11, 308}$=0.75, p>.05). No difference was found for the first trial between the retention and transfer tests.

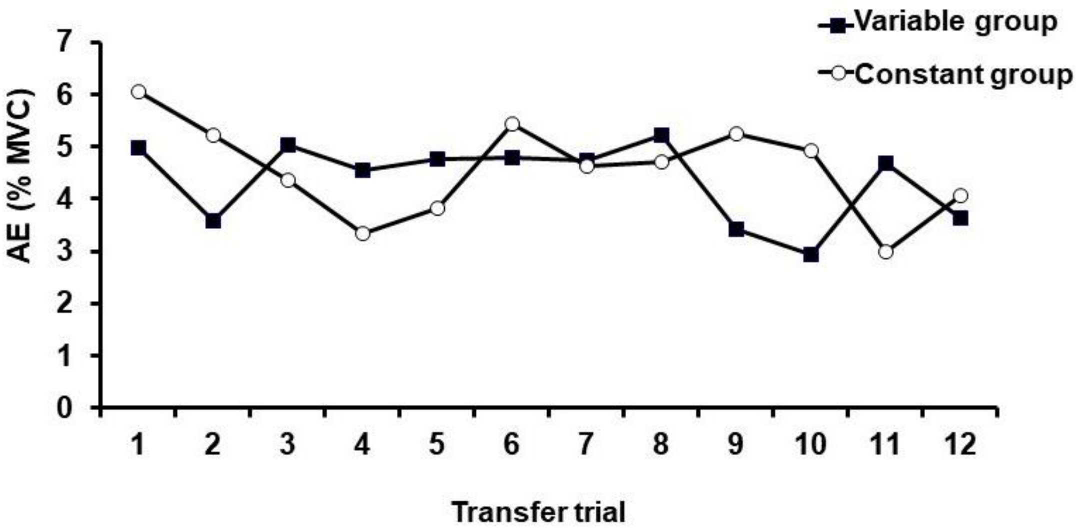

Figure 9. Mean absolute error in individual trials of transfer test. The vertical axis shows the errors in % of MVC.

A 2 groups × 3 blocks (variable/constant × last acquisition block/retention/transfer) ANOVA showed significant main effects for both group ($F_{1, 28}$=6.81, p<.05) and block ($F_{2, 56}$=28.96, p<.01), with a significant group × block interaction ($F_{2, 56}$=5.16, p<.05). Subsequent simple main effect tests of the interaction showed that the difference between the two groups was significant in the last block of acquisition (p<.01), but was not significant in either the retention or transfer tests. Subsequent multiple comparison tests showed that the constant group produced significantly larger errors in the retention test than in the last block of the acquisition (p<.05) and produced significantly larger errors in the transfer test than in the retention test (p<.05). The difference between the last acquisition block and the retention test results of the variable group was not significant, indicating that the variable group provided similar performance in the last acquisition block and the retention test 24 hours later. But the variable group produced significantly larger errors in the transfer test than in the last acquisition block (p<.05).

4.1.3.2.2 Constant error

A two-way ANOVA (2 groups, 16 blocks) was performed on CE data on acquisition. The mean constant errors are plotted on Figure 10. No significant main effect for group was found in the acquisition session ($F_{1, 28}$=1.54, p>.05). The analysis indicated a significant main effect for blocks ($F1_{5, 420}$=8.39, p<.01). Subsequent multiple comparisons on acquisition blocks indicated that the first block was different than all other blocks.

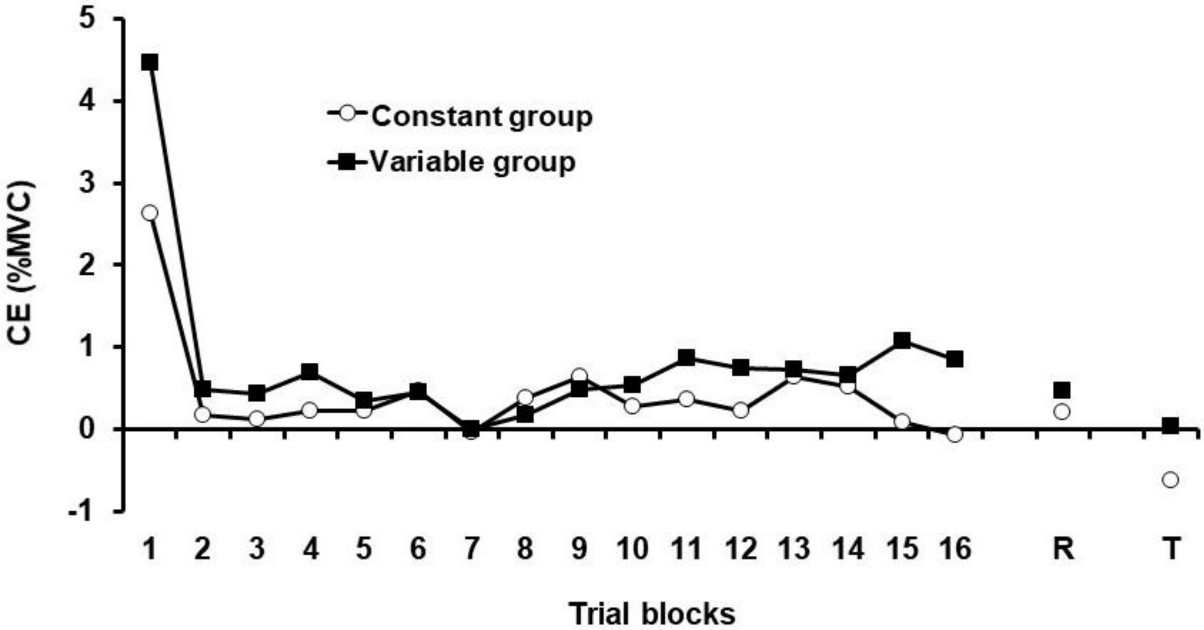

Figure 10. Mean constant error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

A two-way ANOVA (2 groups, 12 trials) performed on retention data indicated no significant main effect for groups ($F_{1, 28}$=0.17, p>.05). The analysis indicated a main effect for trials ($F_{11, 308}$=5.3, p<.01). Subsequent multiple comparisons showed that the first trial significantly differed ($F_{11, 308}$=5.3, p<.01) from the other trials (Figure 11.).

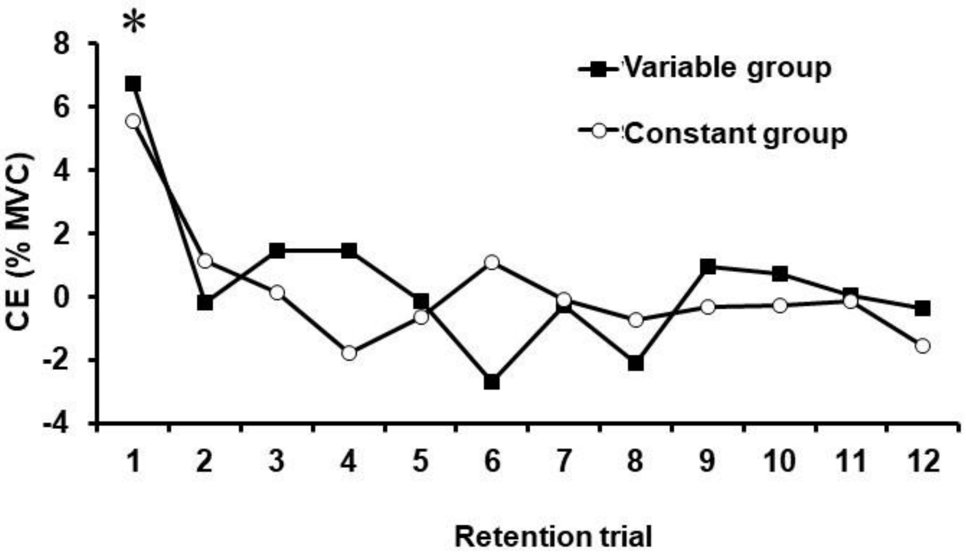

Figure 11. Trial-by-trial mean constant error in retention test. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

A two-way ANOVA (2 groups, 12 trials) performed on transfer data indicated that neither the main effect for group ($F_{1, 28}$=0.78, p>.05) nor the main effect for block ($F_{11, 308}$=0.6, p>.05) was significant. Using a t-test, no difference was found between the first trials of the retention and transfer tests (Figure 12.).

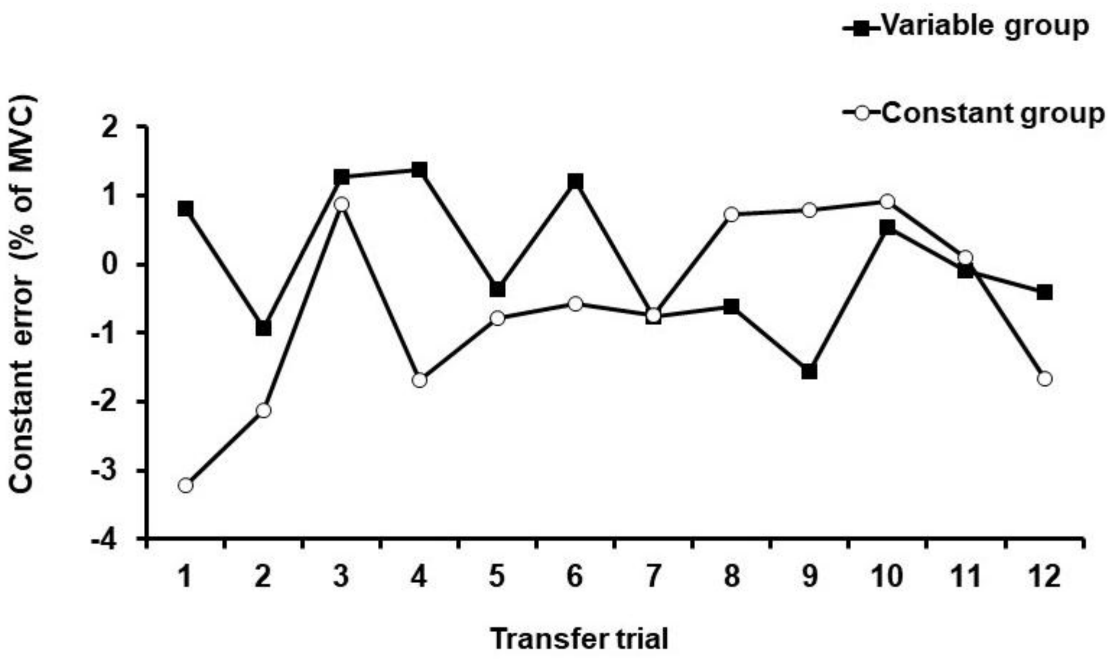

Figure 12. Trial-by-trial mean constant error in transfer test. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

A 2 groups × 3 blocks (variable/constant × last acquisition block/retention/transfer) ANOVA performed on constant error data indicated that either the main effect for group ($F_{1, 28}$=2.83, p>.05) and main effect for block ($F_{2, 56}$=1.57, p>.05) was not significant.

4.1.3.2.3 Variable error

A two-way ANOVA (2 groups, 16 blocks) was performed on VE data of acquisition. The mean variable errors are plotted on Figure 13. The analysis indicated that in the acquisition trials both the main effects for group ($F_{1, 28}$=471.1, p<.01) and the main effect for block ($F_{15, 420}$=28.53, p<.01) were significant. Subsequent multiple comparison tests indicated that the variable condition resulted in larger acquisition errors than the constant condition. Block 1 was different from all other blocks, which, in turn, did not differ from each other in the later phase of acquisition.

A 2 groups × 3 blocks (variable/constant × last acquisition block/retention/transfer) ANOVA performed on variable error data indicated a significant main effect for group ($F_{1, 28}$=23.61, p<.01) and a significant group x block interaction ($F_{2, 56}$=27.82, p<.01). The main effect for block was not significant ($F_{2, 56}$=2.99, p<.1). Subsequent analyses of the interaction indicated that the difference between the two groups was significant in the last block of acquisition (p<.01), but was not significant in the retention and transfer tests. Subsequent multiple comparisons showed that the constant group produced significantly larger errors in the retention test than in the last block of acquisition (p<.05) and produced significantly larger errors in the transfer test than did in the retention test (p<.05). The difference between the last acquisition block and the retention test results of the variable group was also significant (p<.05) indicating that the participants in the variable group improved their consistency. The difference between the retention and transfer data of the variable group did not show significant difference (p>.05), indicating that the variable group provided similar performance in both retention and transfer tests.

Taking together, results indicated that the variable practice condition resulted in larger acquisition errors in terms of magnitude errors and consistency than the constant condition. Difference between the two practice schedules also appeared in retention and transfer ability. While constant practice schedule resulted in deteriorated retention and transfer performance compared to end-of-practice performance, variable practice schedule came to retain performance achieved by the end of practice session.

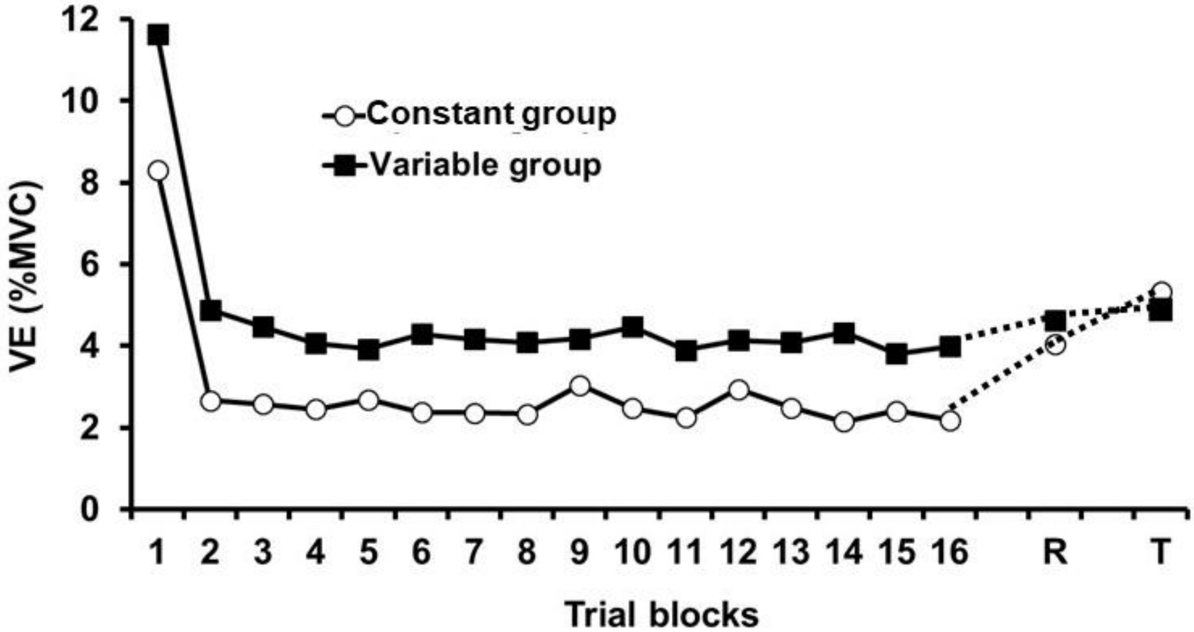

Figure 13. The mean variable error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

4.1.4 Summary of results in Experiment 1 and Experiment 2

The results of both Experiment 1 and Experiment 2 indicated that the groups which practiced several variations of the isometric hand grip force production task during the acquisition phase (variable group) did not provide a better performance in retention and transfer tests than the groups which practiced merely one variation of the task throughout the acquisition phase (constant group). This phenomenon was found in all aspects of performance examined in the present experiments. That is, overall error level, bias indicating overshoot or undershoot and consistency of performance in retention and transfer tests, did not show difference based on the difference practice schedule.

Although the variable group did not show superior performance to the constant group in either the retention or transfer tests, the experience of several variations during acquisition may have caused an effective retention of the performance level acquired at the end of the practice. This was indicated by the lack of significant difference between the last block of acquisition and the retention test for the variable group both in AE and VE, whereas the constant group produced a significantly larger mean AE and VE in the retention test than those in the last block of acquisition. This is consistent in part with the variability of practice hypothesis, although it is not as clear as reported by Shea and Kohl (1990, 1991).

In conclusion, the results of the present studies indicated that variable practice may be good for the retention for at least 24 hours of a constant performance level acquired at the end of a practice session, whereas constant practice may result in deterioration. This is partially consistent with the variability of practice hypothesis, although the two groups did not significantly differ in the absolute performance level for retention and transfer. The lack of a significant difference between the two groups, namely, the absence of a clear paradoxical feature of the variability of practice, may arise from ceiling/floor effects due to the nature, such as familiarity and difficulty, of the task used in the present study (Vámos & Imanaka, 2007).

4.2 Experiment 3. Force discrimination in active isometric hand grip force production

4.2.1 Introduction

The present experiment was conducted in order to find appropriate tasks in the means of difficulty in later motor learning experiments. The aim was to characterize the discrimination threshold for an isometric hand grip force production task to be able to choose force level differences near or below the threshold in following motor learning experiments. The difference threshold is the smallest difference between two stimuli that is required to detect them as different. In other words, it is a measure of the smallest detectable difference (just noticeable difference, JND) between two stimuli (Colman, 2015). Basically, it answers the psychophysical question: How different must two stimuli be from each other in order to detect them as different stimuli (Sekuler & Blake, 2004). Attempts to define the discrimination threshold in a force production task have been described in the literature previously (Table 2.)

	Task	JND
Brodie & Ross (1984)	weight lifting	9-13%
Brodie & Ross (1985)	weight lifting	6.1%
Jones (1989)	elbow flexion	5-9%
Pang et al. (1991)	pinch against resistance	5-10%
Allin et al. (2002)	metacarpophalangeal joint flexion	10%

Table 2. Discrimination threshold values in various motor tasks that are based on force production. Thresholds are expressed in JND % compared to the standard stimuli.

While the above tasks use weight discrimination or dynamic muscle contraction, ours was a static/isometric task. In contrast to dynamic muscle contraction, the length of the muscle and the joint angle do not change during isometric force exertion. As a consequence, less input from the dynamic afferents and spatial information about the movement is processed (Kenney, Wilmore, Costill, & Wilmore, 2012). It raises the question if these differences affect the discrimination threshold level.

Measurements of the discrimination threshold have been previously carried out by matching forces or weight by the two body sides. (Jones, 1989; Jones & Hunter, 1982). This procedure has the advantage of simultaneous force production of the standard and the comparison stimuli. On the other hand, it does not take into account the possibility of different motor status of the two body sides that may affect perception (Jones & Hunter, 1982; Simon, Kelly, & Ferris, 2009). This is often the case in students with special needs (cerebral palsy or peripheral nerve damage) or in rehabilitation settings (e.g., post stroke clients with hemiparesis). In these cases the different muscle status and sensory deficit between the sides make it difficult or impossible to use the comparison of the two body sides as a reliable measure of force perception (Simon et al., 2009). In the present study, we sought to develop a novel method that enables the measurement of force discrimination threshold using one body side at a time. Our second goal was to to define the discrimination threshold for isometric hand grip force production. My hypothesis was that discrimination threshold for isometric force production would be similar or higher than in isotonic force production tasks.

4.2.2 Method

4.2.2.1 Participants

9 healthy university students participated in the experiment; 4 males and 5 females.

4.2.2.2 Apparatus

The apparatus used for data acquisition consisted of an isometric hand grip dynamometer (Takei T.K.K. 5710) connected to a data acquisition box (National Instruments BNC 2120), which was connected to a notebook personal computer (PC, NEC). A software run on the PC was programmed (in LabVIEW 6.0) to read and store force data. A second monitor was connected to the PC in order to provide visual feedback about the magnitude of force produced by the participants. The online visual feedback served the purpose of producing the required target forces. The force exerted in a given trial was calculated as the average of the three-seconds-period of force production, which started when the exerted force first reached the required target force level after the subject began to exert the force and enhanced his/her force gradually. Target force level means the required level of force exertion in a given task.

4.2.2.3 Procedure

Participants were asked to sit comfortably in a chair next to a table. The computer monitor was situated so that the screen was in plain view, and the isometric hand grip dynamometer was positioned so that it could be comfortably gripped with the right hand.

Measurements of maximum voluntary contractions (MVC) performed for four seconds by the right hand were recorded three times at the start of the experiment. Maximum force was defined as the average of the three contractions.

In order to determine the discrimination threshold, the psychophysical method of constant stimuli was applied. Participants were asked to exert two forces successively, a standard and a comparison force level, each for three seconds in each comparison. The inter-trial interval between the two consecutive force production phases was held constant (3s). When participants finished the two force productions they made a judgment about which of the two forces felt heavier, the first or the second one. The answer was recorded by the author. The standard force was 14% of the MVC of the participant and remained the same in each compare block during the experiment. Comparison forces ranged over a set of values from block to block and were 14 ± 0.5, 1, 1.5, 2, and 2.5% of the MVC. The order of comparison forces from block to block was randomized, and the location of the standard force within one block (whether the standard force was the first or the second force production to be compared) was also randomized in order to prevent the participants from learning it.

In order to produce the adequate target forces, an online colour feedback indicated on the computer monitor, parallel with the force production, whether the exerted force of the participant matched to the target force specified by the experimenter or not. Green colour appeared in the feedback window if the exerted force matched to the target force, red if the applied force was too strong, and grey if too weak (Figure 14.). The computer was programmed so that the range in which green colour appeared was between the given target force ± 0.25% of the MVC of the participant.

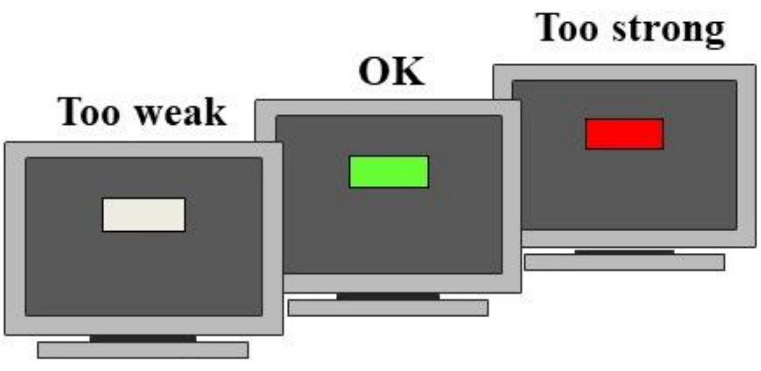

Figure 14. Real-time visual feedback provided to participants during discrimination threshold measurement to keep force production in the target zone. Participants adjusted their force production to reach and keep within the green zone (target force level ± 0.25% MVC). Appearance of grey colour indicated that the force exertion was too weak and red colour indicated that force production was too strong.

For the participant two signals at the same time indicated the beginning of the force production within a compare block. One was a sound signal, and the other was the appearance of number 1 on the computer monitor in front of the participant, indicating the serial number of the first required force production. After the signals, the participant increased his/her force gradually until the colour in the feedback window changed from grey to green. From that moment the task of the participant was to keep exerting the force appropriate of the green colour (to exert a force level which kept the green colour on the monitor) for 3s permanently. The end of the force production was signalled by a sound signal different from the start indicator and by the disappearance of the serial number 1. After a 3s rest period the start indicator sound and the appearance of number 2 signed the beginning of the second force production. The task of the participant was again to exert a force level which kept the green colour on the monitor for 3s permanently. After finishing the second force exertion, the participant made a judgment about which of the two forces felt heavier.

To become familiar with the task, participants made at least ten comparisons before the experimental trials began. To avoid fatigue, a rest period was interpolated between the blocks after every 10 comparisons and in addition participants could take a rest during the experiment whenever they felt it necessary.

Since the force to be perceived was produced actively by the participant, as a result, he/she could not always exert the required target force accurately for three seconds. For data analysis only those comparison block results were used, in which the exerted force of the standard level was within the range of 14 ± 0.25% of the MVC. Data outside of this range were discarded.

4.2.3. Results and discussion

According to the method of constant stimuli, the discrimination threshold was obtained at the difference category in which the proportion of the correct answers was 75% (Figure 15.). The results of Experiment 3 showed that the discrimination threshold for the isometric hand grip force production task was in the difference range of 1.75-2.25% MVC when a force level of 14% of MVC was used as a standard stimulus (which was compared by different stimuli). In other words, the threshold was found between 12,5-16% of the constant stimuli.

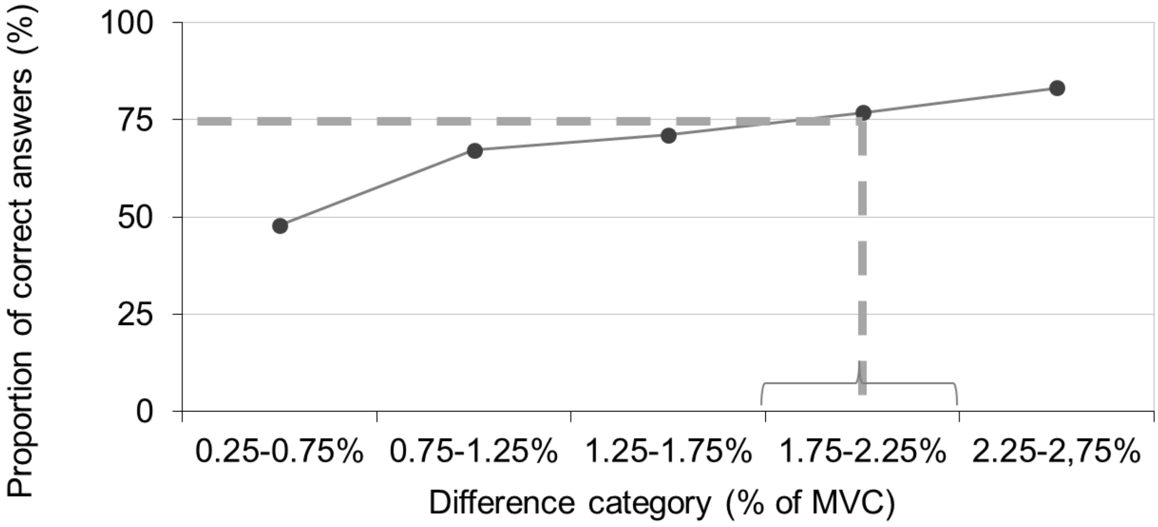

Figure 15. Discrimination threshold in the means of JND compared to a 14% of maximum voluntary contraction (MVC) standard stimulus. The proportion of correct answers against the difference between the two successive force productions experienced by the participants is plotted. Due to the nature of the task, threshold is expressed as a difference range 1.75-2.25% MVC.

It supported the hypothesis that the discrimination threshold for isometric force production is similar or higher than in isotonic force production tasks (Vámos, Berencsi, & Imanaka, 2015). Previous studies regarding force or weight discrimination found the discrimination threshold level between 5-12% of the constant stimulus. The upper limit of 12% in these studies corresponds to the lower end of the threshold range in our experiment. A possible reason for this is the difference in the isometric and isotonic nature of the tasks used in these experiments. For perception of force, humans use both sense of force (sensory feedback from periphery e.g. Golgi tendon organs or tactile receptors) (Jones & Piateski, 2006) and the sense of effort (e.g., activity in motor cortices or descending motor commands) (Carson, Riek, & Shahbazpour, 2002; Simon et al., 2009). Recruitment of motor units and cortical motor control of static and dynamic tasks show a differential pattern (Neely, Coombes, Planetta, & Vaillancourt, 2013) and there is also a different pattern in sensory feedback (Lundy-Ekman, 2013). Tasks in previous literature involved dynamic components and with one exception were gross motor tasks. In contrast, our task was an isometric fine motor task. These differences in task nature may have served as a possible component for difference in the sensory threshold level. Furthermore, estimation of the magnitude of force depends not only on the dynamic or static nature of the task. It is also defined by the muscle groups involved in the task: the same force produced by hand muscles is perceived greater compared to when it is produced by elbow muscles (Jones, 2003). Moreover, the muscle length during the task also influences force perception (Cafarelli & Bigland-Ritchie, 1979). These numerous factors may have contributed to the altered threshold level compared to previous studies and confirm the necessity of task specific threshold measurement carried out in this study.

4.3 Experiment 4

4.3.1 Introduction

A possible reason for the lack of variability effect in Experiments 1-2 was the familiarity of the task nature. After the discrimination threshold was characterized for the isometric hand grip force production task in Experiment 3, adjustment of task difficulty in terms of discrimination between target forces became possible in the following experiment. Here, difficulty is enhanced by decreasing the difference between adjacent target force levels in the variable practice group. That is, discrimination between target force levels becomes more challenging in the variable practice group. In Experiment 4, I planned to examine the effect of variability of practice using an isometric hand grip force production task with force level differences below the discrimination threshold gained in Experiment 3. In the present study, immediate and delayed retention and transfer tests, as well as the absence and presence of feedback during testing were administered to reveal if they affect the appearance of group differences. My hypothesis was that increasing difficulty in the means of decreased inter-target difference but keeping the number of task variations invariable may result in improved performance in terms of retention and transfer in the variable practice group.

4.3.2 Methods

4.3.2.1 Participants

Sixteen university students (11 males and 5 females) randomly selected into two groups. Mean age was 24.6 years (*SD* = 3.4 years).

4.3.2.2 Apparatus

The same apparatus was used as in Experiment 1 and 2.

4.3.2.3 Procedure

Following maximum force measurement participants were randomly assigned into two practice groups. In the constant group, participants practiced a single force level of 14% MVC, called a criterion force (Task C). The variable group practiced five task variations in a randomized order with the smallest difference between the tasks being 1% of MVC (Table 3.).

Task variations during acquisition	Variable	Constant
Task A	12% of MVC	
Task B	13% of MVC	
Task C (criterion)	14% of MVC	14% of MVC
Task D	15% of MVC	
Task E Transfer in Transfer out	16% of MVC 15.5% MVC 17% MVC	

Table 3. Target forces for variable and constant practice groups in Experiment 4.

The way of force production by the participants, the amount of practice, the way of providing feedback were identical to Experiment 2. 10 minutes and 24 hours after the acquisition session, retention and transfer tests were administered with first providing no feedback on any trial, followed by a repeated test by providing feedback. The task variation tested in the retention was the Criterion task (Task C) which was practiced by each group during the acquisition phase. There were two transfer tasks: a new parameter variation within the practice range (Transfer in) and a new parameter variation outside the practice range (Transfer out).

4.3.3 Results

4.3.3.1 Absolute error

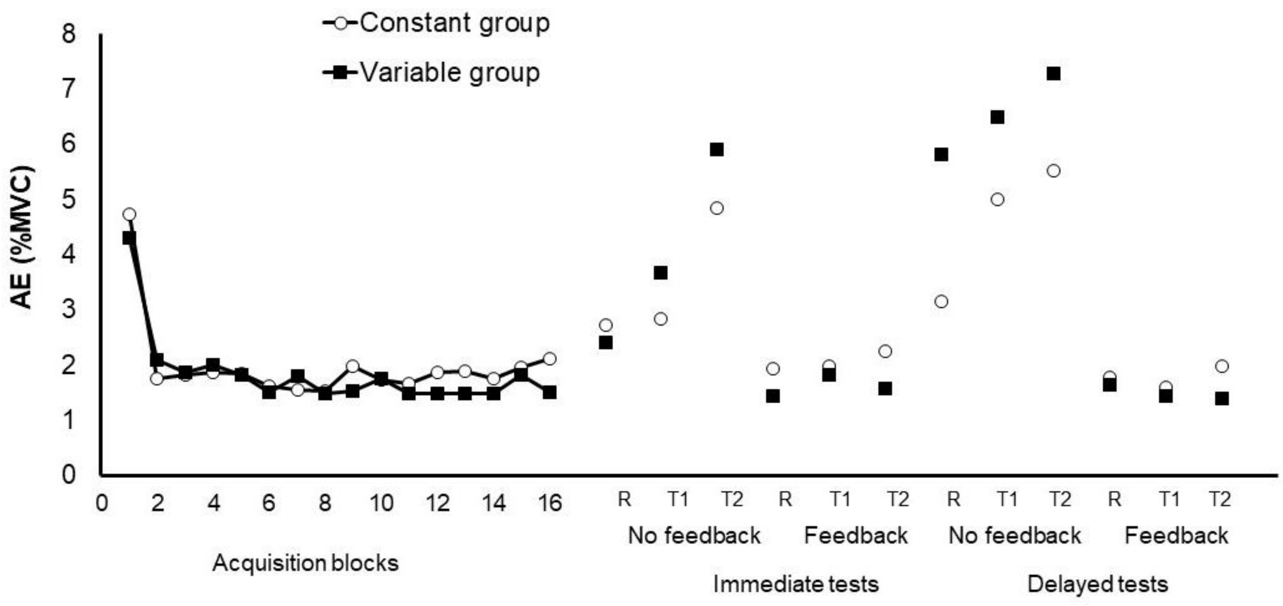

Figure 16. Mean absolute error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16, immediate and delayed tests of retention (R) and transfer (T) with and without feedback. T1 force level was within and T2 was outside of the practice range. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

Mean AEs are plotted on Figure 16. A two-way ANOVA (2 groups × 16 blocks of acquisition, immediate and delayed retention and transfer tests with and without feedback) performed on AE data showed no significant main effects for group ($F_{1, 14}$=0.071, p>.05). Main effect for block was significant ($F_{27, 398}$=14.918, p<.01) with no significant interaction (p>.05). Subsequent multiple comparison tests revealed that the variable group did not produce a significantly greater level of error than the constant group during acquisition, retention and transfer tests (p>.05). There was a significant learning effect in terms of improvement between the first and last blocks of acquisition (p<.05). Regarding retention, performance in immediate retention with and without feedback and delayed retention with feedback was better than first block performance (p<.05). In comparison with the last acquisition block, performance deteriorated in immediate and delayed retention tests in the absence of feedback (p<.05). In terms of transfer, performance was significantly improved in the presence of feedback in all transfer tests (p<.05) but not in the absence of feedback (p>.05) compared to the first block.

4.3.3.2 Constant error

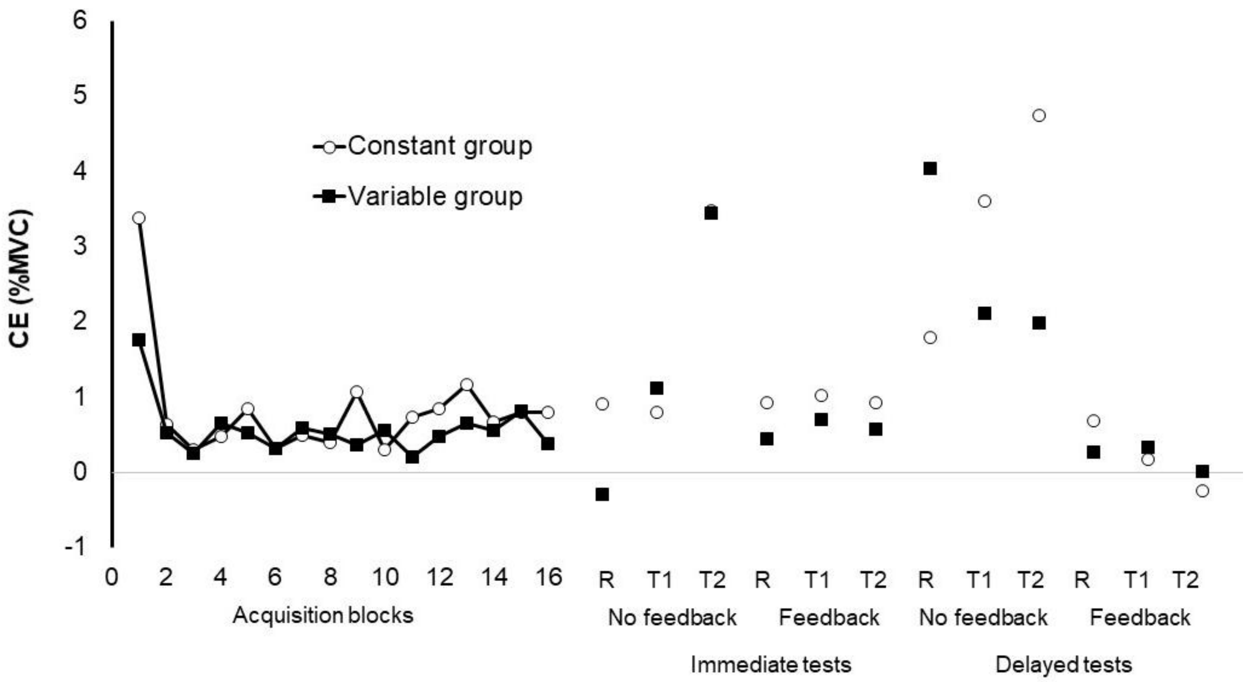

Figure 17. Mean constant error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16, immediate and delayed tests of retention (R) and transfer (T) with and without feedback. T1 force level was within and T2 was outside of the practice range. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

Mean CEs are plotted on Figure 17. A two-way ANOVA (2 groups × 16 blocks of acquisition, immediate and delayed retention and transfer tests with and without feedback) performed on CE data showed no significant main effects for group ($F_{1, 14}$=0.311, p>.05). The main effect for block was significant ($F_{27, 398}$=2.847, p<.01) with no significant interaction (p>.05). Subsequent multiple comparisons revealed that the variable group did not produce a significantly greater level of error than the constant group during acquisition, retention and transfer tests (p> .05). There was a significant learning effect in terms of improvement between the first and last blocks of acquisition (p<.05). Regarding retention, performance was preserved in all retention tests regardless of time since the last block practice and feedback condition (p> .05). However, there was a tendency for overshoot in the absence of feedback in the retention and transfer tests, it did not reach statistical significance (p>.05).

4.3.3.3 Variable error

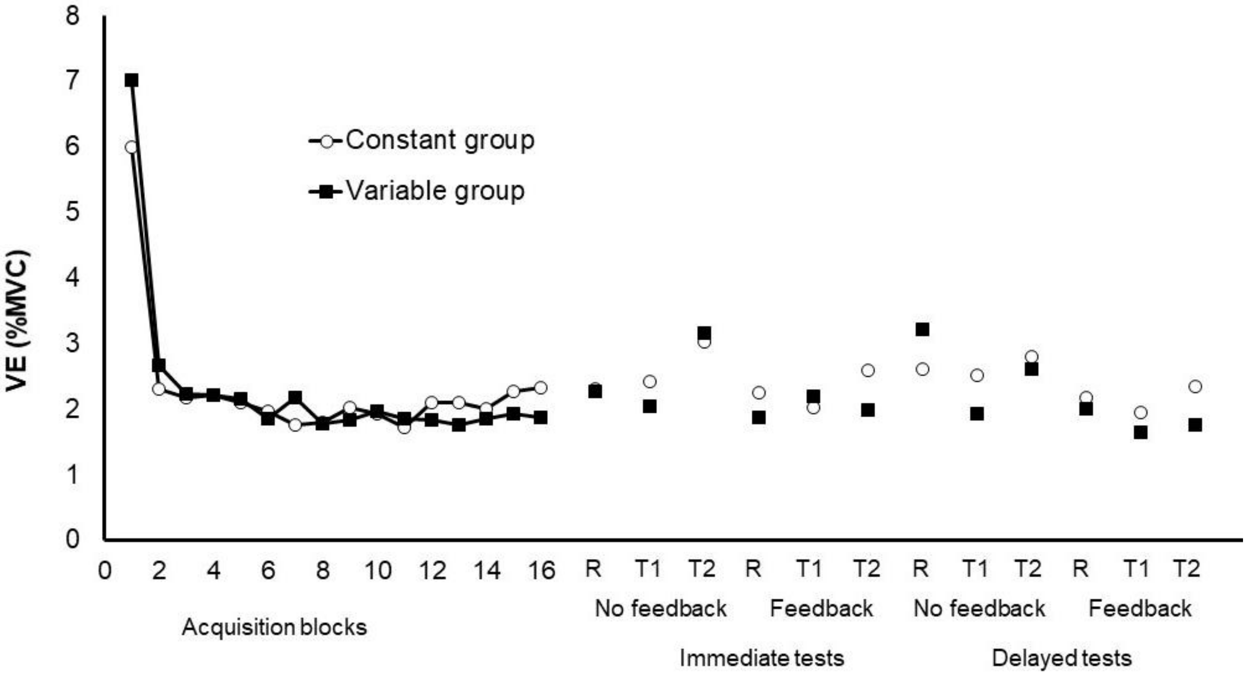

Figure 18. Mean variable error. The horizontal axis shows acquisition trial blocks from blocks 1 to 16, immediate and delayed tests of retention (R) and transfer (T) with and without feedback. T1 force level was within and T2 was outside of the practice range. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

Mean VEs are plotted on Figure 18. A two-way ANOVA (2 groups × 16 blocks of acquisition, immediate and delayed retention and transfer tests with and without feedback) performed on acquisition showed no significant main effects for group ($F_{1, 14}$=0.035, p>.05). The main effect for block was significant ($F_{27, 398}$=11.886, p<.01) with no significant interaction (p>.05). Subsequent multiple comparison tests revealed that the variable group did not produce a significantly greater level of error than the constant group during acquisition, retention and transfer tests (p>.05). There was a significant learning effect in terms of improvement between the first and last blocks of acquisition (p<.05) and the first block of acquisition and all retention and transfer tests (p<.05). Regarding retention and transfer tests, the immediate transfer out test without feedback and the delayed retention test without feedback showed significantly less consistent performance compared to other learning tests ($p<.05$). No further difference between tests was found ($p>.05$).

4.3.3.4 Summary of results in Experiment 4

The main finding of Experiment 4 was that decreasing variability in terms of decreased inter-target difference below threshold and decreased range of target forces resulted in abolished difference between variable and constant groups in all aspects of the motor task, including overall error level and consistency. This phenomenon was found both during acquisition, retention and transfer (Vámos & Imanaka, 2015).

A further finding was that in the presence of feedback during testing, performance may become more accurate and consistent. This is in accordance with previous literature (Schmidt & Lee, 2011). Furthermore, this effect can be found irrespective of the time of testing (immediate or delayed feedback). Since our goal was to find conditions that may promote the dissociation of learning effect due to different learning conditions, the application of no feedback condition during testing was favourable in further experiments.

4.4 Experiment 5

4.4.1 Introduction

Experiment 4 showed that decreasing practice variability in terms of intertarget difference and range of the practiced parameter result in a learning pattern similar to the constant practice. In a following experiment, our goal was to examine the effect of varying inter-target difference and range of parameters on acquisition performance, retention and transfer. Our hypothesis was that if the schema theory holds, increased variability with a broader range of force production levels experienced in practice would be advantageous in subsequent retention and transfer tests.

4.4.2 Methods

4.4.2.1 Participants

Participants were thirty-two students (24 males and 8 females, 2 females and 6 males in each group). Mean age was 20.7 years (SD = 2.5 years). Participants were assigned to one of the four practice groups in a random order.

4.4.2.2 Apparatus

The apparatus used in the present experiment was identical to that of Experiments 1, 2 and 4.

4.4.2.3 Task and practice groups

Following maximum force measurement participants were assigned into two practice groups. In the constant group, participants practiced a single force level of 25% MVC, called a criterion force. The three variable groups practiced the criterion force and four additional variations of it with three different inter-target differences (2.5%, 5%, and 10% of MVC). The variable 2.5% group performed 20, 22.5, 25, 27.5, and 30% of MVC; the variable 5% group, 15, 20, 25, 30, and 35% of MVC; and the variable 10% group, 5, 15, 25, 35, and 45% of MVC, in a random order (i.e., random schedule). Increasing the inter-target difference aimed to broaden the range of variations of force levels experienced during practice.

4.4.2.4 Procedures

Participants were asked to sit comfortably in a chair in front of a computer display situated in plain view of the participant. The isometric hand grip dynamometer was positioned so that participants could comfortably grip it with the right hand. In the acquisition (practice) session, both the constant and the four variable groups performed the acquisition session, which consisted of 16 blocks of 20 trials with each block of 20 trials being further divided into 4 sub-blocks, for a total of 320 trials.

Twenty-four hours after the acquisition session, both the retention and transfer tests were conducted. In the retention test, participants were required to produce 20 trials of the criterion force production (25% MVC). The transfer test consisted of 20 trials of a novel force production, namely 55% of the MVC, which was not experienced during the acquisition session. No feedback about the magnitude of the produced force was provided on the computer screen during the retention and transfer tests.

4.4.2.5 Dependent variables

For dependent variables, AE, VE, CE, and E were calculated.

4.4.2.6 Statistical analyses

To evaluate performance during the acquisition session, a two-way analysis of variance (ANOVA), with independent variables of the type of practice (constant, variable 2.5%, variable 5%, and variable 10%) and block (16 blocks), was performed on each dependent variable with repeated measures on block. To evaluate performance in the retention and transfer tests, a two-way ANOVA, with the independent variables of type of practice (4 groups) and block (the last practice block, retention test, and transfer test), was performed on each dependent variable, with repeated measures on block factor. Multiple comparisons with LSD were performed when necessary.

4.4.3 Results

4.4.3.1 Absolute error

For the mean AEs (Figure 19.), a two-way ANOVA (4 groups × 16 blocks) showed significant main effects for both group ($F_{3, 28} = 4.42$, $p < .05$) and block ($F_{15, 420} = 15.53$, $p < .01$), with no significant interaction between group and block ($F_{45, 420} = 0.94$, $p > .05$). During the 16 acquisition-trial blocks, the variable 10% group produced significantly greater AEs than the constant group and the variable 2.5% and variable 5% groups. The AE differences between constant, variable 2.5%, and variable 5% groups were not significant during the 16 acquisition-trial blocks. A subsequent multiple-comparisons test revealed that the first ($p < .01$) and second ($p < .05$) blocks showed a significantly greater AE than those in all other blocks.

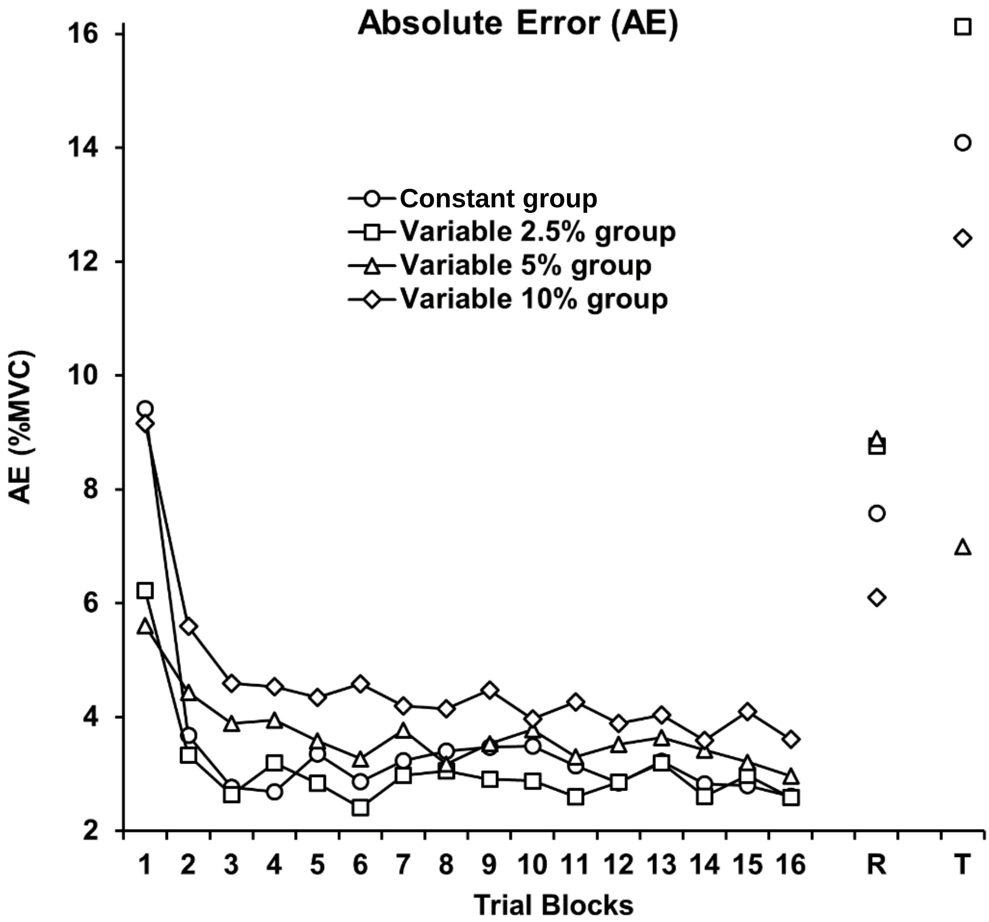

Figure 19. Mean absolute error for acquisition, retention, and transfer performance for the constant and the three variable groups. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

In the course of analysis of the last block of acquisition, retention and transfer tests for AE, ANOVA showed no significant main effect for group ($F_{3, 28} = 1.93$, $p > .05$) but significant main effect for block ($F_{2, 56} = 38.98$, $p < .001$), with a significant group × block interaction ($F_{6, 56} = 2.79$, $p < .05$). Subsequent simple main effect tests showed a significant simple main effect for group at both the last block of acquisition ($F_{3, 28} = 3.18$, $p < .05$) and at the transfer test ($F_{3, 28} = 3.44$, $p < .05$), with no significance at the retention test ($F_{3, 28} = 0.72$, $p > .05$). For the group difference at the transfer test, the AE at the variable 5% group showed a significantly less AE than those at other groups ($p < .05$), with no significant difference appearing for the other three groups ($p > .05$).

Subsequent multiple comparisons showed that both the constant and the variable 2.5% groups produced a significantly larger AE at the retention test than at the last acquisition block ($p < .05$) and a significantly larger AE at the transfer test than at the retention test ($p < .05$). For the variable 5% group, they produced a significantly larger AE at the retention test than at the last acquisition block ($p < .05$), whereas the AE at the transfer test did not differ from the last acquisition block ($p > .05$), with no significant AE difference for the retention and transfer tests ($p > .05$). The difference of AE of the variable 10% group at the last acquisition block and at the retention test was not significant ($p > .05$). Furthermore, the variable 10% group produced a significantly larger AE at the retention test than at the last acquisition block ($p < .05$), with a significantly larger AE appearing at the transfer test than at the retention test ($p < .05$).

4.4.3.2 Constant error

For the mean CEs (Figure 20.), a two-way ANOVA (4 groups × 16 blocks) showed a significant main effect for block ($F_{15, 420} = 5.12$, $p < .01$) but did not show any significance for group ($F_{3,28} = 0.84$, $p > .05$), with the group × block interaction being not significant ($F_{45, 420} = 0.96$, $p > .05$). A subsequent multiple-comparisons test for the 16 acquisition blocks showed that the mean CE of the first block was larger than those of all other blocks ($p < .05$).

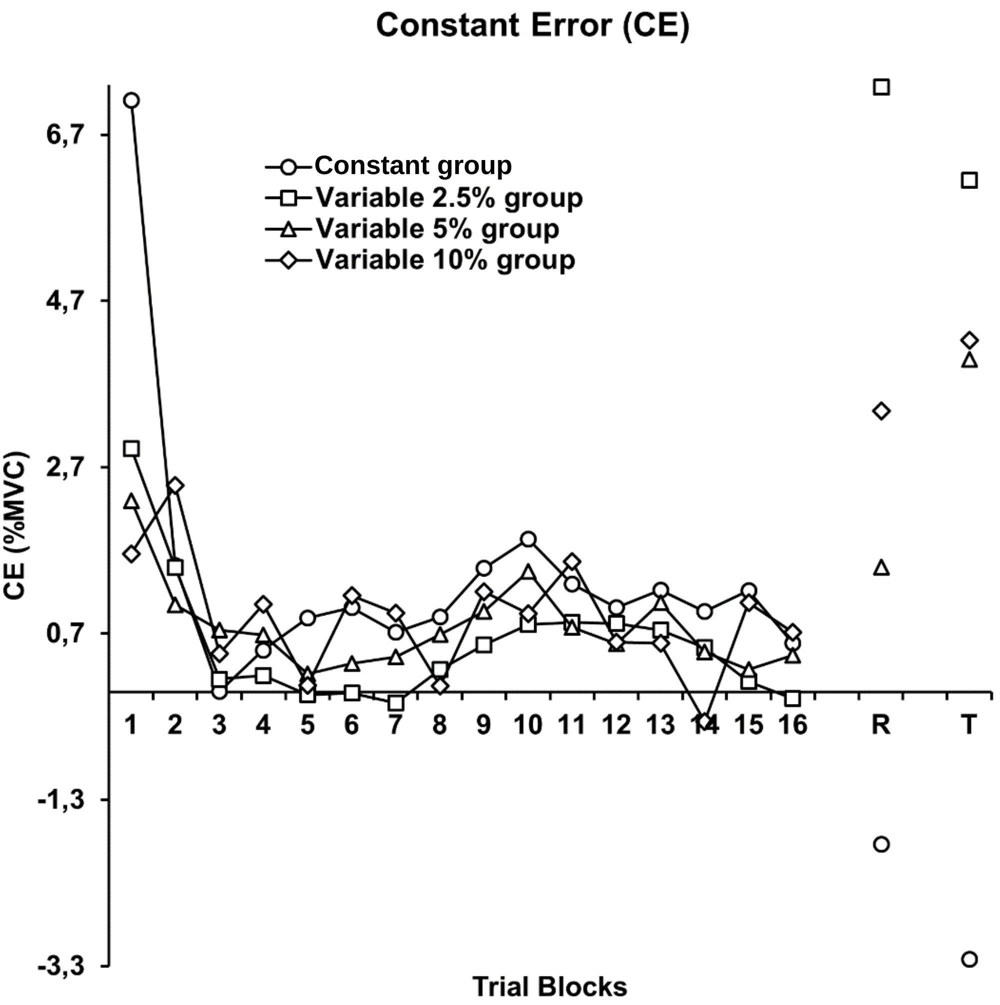

Figure 20. Mean constant error for acquisition, retention, and transfer performance for the constant and the three variable groups. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

With regard to performance in the last block of acquisition, retention and transfer tests, a 4×3 (group × block) ANOVA showed no significant main effect for either group ($F_{3, 28} = 1.41$, $p > .05$) or block ($F_{2, 56} = 0.74$, $p > .05$), with no significant interaction for CE.

4.4.3.3 Variable error

In relation to the mean VEs (Figure 21.), a two-way ANOVA (4 groups × 16 blocks) showed significant main effects for both group ($F_{3, 28} = 6.52$, $p < .01$) and block ($F_{15, 420} = 26.35$, $p < .01$). The interaction between group and block was not significant ($F_{45, 420} = 1.51$, $p > .05$). In the 16 acquisition trial blocks, the variable 10% group generally produced significantly greater VEs than the constant, variable 2.5%, and variable 5% groups. A subsequent multiple comparisons test revealed that the first block showed a significantly greater mean VE than all other blocks ($p < .05$).

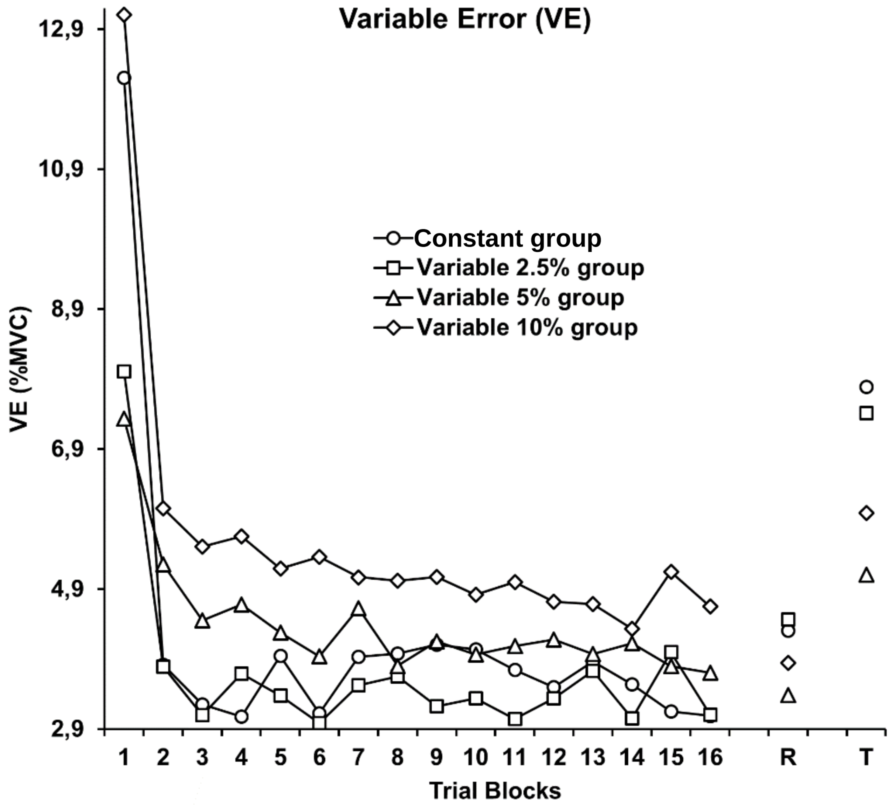

Figure 21. Mean variable error for acquisition, retention, and transfer performance for the constant and the three variable groups. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

The last block of acquisition, retention and transfer test performance analysis by a 4×3 (group × block) ANOVA showed no significant main effect for group ($F_{3, 28}$ = 1.89, p > .05) but showed a significant main effect for block ($F_{2, 56}$ = 36.42, p < .01), with a significant group × block interaction ($F_{6, 56}$ = 3.03, p < .05) for VE. Subsequent simple main effects tests for group showed a significant simple main effect at the last acquisition block ($F_{3, 28}$ = 4.82, p < .01) but not at either the retention ($F_{3, 28}$ = 1.06, p > .05) or transfer ($F_{3, 28}$ = 2.78, p > .05) tests. Multiple comparisons performed at the last acquisition block showed that the VE for the variable 10% was significantly larger than for the other three groups (p > .05), which did not differ from each other (p > .05).

Subsequent multiple comparisons between three blocks per group showed that both the constant and variable 2.5% groups produced significantly larger VEs at the transfer test than at the last acquisition block (p < .05), with significantly larger VEs at the transfer test than at the retention test (p <.05), which did not significantly differ from the VE at the last acquisition block (p > .05). Multiple comparisons respectively performed for the variable 5% and 10% groups showed that VEs at both the retention and transfer tests did not significantly differ from those at the last acquisition block (p > .05 for all), with the VEs at the transfer test being significantly larger than at the retention test (p < .05 for all). This indicated that both the variable 5% and 10% groups performed similar variable errors for the last acquisition block, the retention, and transfer tests.

4.4.3.4 Total error

For the mean Es (Figure 22.), a two-way ANOVA (4 groups × 16 blocks) showed significant main effects for both group ($F_{3, 28}$ = 4.18, p < .05) and block ($F_{15, 420}$ = 20.28, p < .01), with no significant interaction between group and block ($F_{45, 420}$ =

1.17, $p > .05$). During the 16 acquisition-trial blocks, the variable 10% group produced significantly greater Es than the constant, variable 2.5%, and variable 5% groups. The E differences between constant, variable 2.5%, and variable 5% groups were not significant during the 16 acquisition-trial blocks. A subsequent multiple-comparisons test revealed that the first two blocks showed a significantly greater E ($p < .05$) than those in all other blocks. Block 16 showed significantly less Es ($p < .05$) than most of the prior blocks.

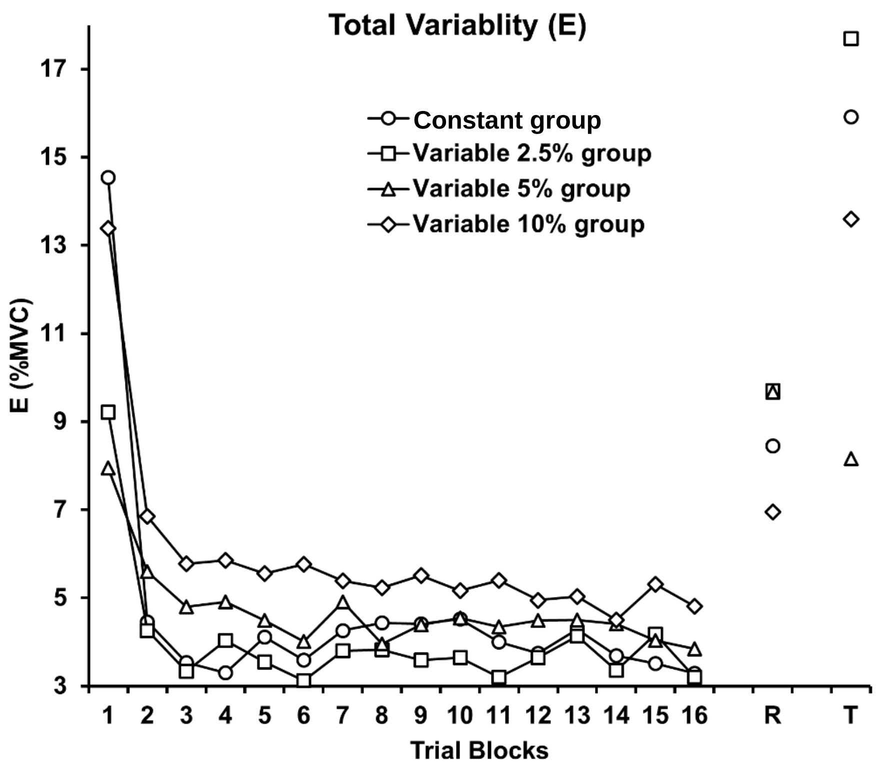

Figure 22. Mean total error for acquisition, retention, and transfer performance for the constant and the three variable groups. The horizontal axis shows acquisition trial blocks from blocks 1 to 16 and the retention (R) and transfer (T) test blocks. The vertical axis shows the errors in % of maximum voluntary contraction (MVC).

For E, a 4×3 (group × block) ANOVA showed a significant main effect not for group ($F_{3,\ 28} = 2.12$, $p > .05$) but for block ($F_{2,\ 56} = 46.07$, $p < .01$), with a significant group × block interaction ($F_{6,\ 56} = 3.34$, $p < .01$). Subsequent simple main effects tests for group showed a significant simple main effect at the last block of acquisition ($F_{3, 28}$ = 4.23, $p < .05$), with E for the variable 10% group being significantly greater than those for the constant and variable 2.5% groups ($p < .05$) but not for the variable 5% ($p > .05$) group. For the retention test, there were no significant group differences ($p > .05$). For the transfer test, there was a significant main effect for group ($F_{3, 28}$ = 4.08, $p < .05$), with the E for the variable 5% group being significantly less than for the constant and variable 2.5% groups ($p < .05$) but not for the variable 10% group ($p > .05$), which showed no significant difference from the other three groups ($p > .05$).

Both the constant and variable 2.5% groups produced significantly larger Es at both the retention and transfer tests than at the last acquisition block ($p < .05$ for all). The constant group produced significantly larger Es at the transfer test than that at the retention test ($p < .05$). Similar to this, the variable 2.5% group showed a marginally significant difference between the retention and transfer tests ($p = .058$). For the variable 5% group, they showed significantly larger Es at both the retention and transfer tests than at the last acquisition block ($p < .05$ for both), with no significant difference for the retention and transfer tests ($p > .05$). For the variable 10% group, the E at the retention test did not significantly differ from that at the last acquisition block ($p > .05$) but the E at the transfer test was significantly larger than at the last acquisition block ($p < .05$), with the E at the transfer test being significantly larger than at the retention test ($p < .05$).

4.4.4 Discussion

Our results showed that the range of experienced force levels (variability) during practice generally determined the amount of errors during practice. Increasing the range size of target forces performed in practice generally increased performance errors during acquisition, such that the highest variability group (i.e., variable 10%) showed the largest amount of errors in AE, VE, and E. In contrast to the variable 10% group, the other three groups (the constant, the variable 2.5% and 5% groups) that practiced the force production task with relatively lower variability (with or less than 5% MVC between target forces) generally resulted in no significant differences in VE, CE, AE or E.

The present results indicated that the variability manipulated by differing the range of force levels during practice did not have a significant influence on recalling the criterion task since there was no significant difference between practice groups in retention test after one day. Furthermore, the group with the highest variability (variable 10% group) that performed with the largest errors during acquisition did not outperform other groups in the retention test. Regarding the transfer test, the groups practicing with the lowest variability (the constant and variable 2.5% groups) showed the poorest performance. Although the variable 5% group experienced a higher variability but resulted in a similar amount of errors to the constant and 2.5% groups during acquisition, this group showed the most superior performance in the transfer test.

4.5 Experiment 6

4.5.1 Introduction

After hemiparetic stroke, one of the most challenging tasks is to regain hand function (Etoom et al., 2016). It includes also learning precise isometric grip force production. This function is crucial for activities of daily living such as grasping and holding objects and manipulating with them. Its impairment is due not only to muscle weakness but also to the decreased sensory and motor control of the affected body side (Jones, 2000; Jones & Piateski, 2006; Kang & Cauraugh, 2015). Recovery of this function therefore should involve regaining sensorimotor control during learning.

In the field of rehabilitation, acquired skills should be retained in the long run. Moreover, they should be generalizable to new circumstances in everyday life (Krakauer, 2006). These functions are affected by practice schedule (Schmidt, 2003) where an advantage of variable practice is that it promotes transfer of learning to new tasks (Shea & Kohl, 1990, 1991). While this paradigm is well established in healthy population (Douvis, 2005; Shea et al., 2001; Sherwood, 1996) studies in the field of rehabilitation are scarce (Krakauer, 2006).

Notwithstanding the benefits of variable practice are not yet well explored in neurorehabilitation, introduction of variability into training schedule is recommended (van Vliet, Matyas, & Carey, 2012). The aim of Experiment 6 is to determine the characteristics and the effects of variable vs. constant practice on the learning process of isometric hand grip force production by the hemiparetic hand following unilateral stroke. My hypothesis was that characteristics of variable practice as compared to constant practice e.g., higher error level during practice, but successful or more effective learning in terms of retention and transfer would be present after hemiparetic stroke.

4.5.2 Method

4.5.2.1 Ethics statement

This study was approved by the Research Ethics Review Board of the National Institute for Medical Rehabilitation (NIMR), Hungary. Date of issue of the Ethical Approval by NIMR was 20. July, 2007.

4.5.2.2 Participants

Participants were hemiparetic stroke patients, all inpatients recruited at NIMR. Recruitment was not continuous due to interrupted availability of the measurement device. Exclusion criteria were sensory aphasia, severe cognitive problems, serious medical condition and severe spasticity of the hand. 36 persons completed the training, 3 patients (n=2 variable, n=1 constant group) dropped out due to training interruption and were excluded from statistical analysis. The 36 participants were assigned into two practice groups matched by age, gender, sensory function and functional status measured by Barthel Index (Table 4.). Sensory testing included tactile and position sense testing of the standard neurologic examination. Participants were not aware of the different practice conditions.

	Constant group n=18	Variable group n=18
Male	12	12
Female	6	6
Age (years)	58.1 (±9.4)	57.5 (±8.4)
Barthel Index	97.1 (±4.2)	97.8 (±3.0)
Dominant hand right	18	17
Affected side right	14	10
Time since stroke (months)	5.8 (±6.9)	3.7 (±4.8)
Sensory impairment	n=9	n=7

Table 4. Participants in the constant and variable practice groups in Experiment 6.

4.5.2.3 Apparatus

Hardware used in Experiment 6 was developed in the European ALADDIN project supported by the European Commission 6th Framework Programme under the grant N.507424. Originally, the ALADDIN Diagnostic Device provided an 'isometric approach' to post-stroke functional measurement (Van Vaerenbergh et al., 2005). The full device is shown in Figure 23. In the present experiment, a finger device (7) was used for the measurement of isometric force production by the I-III. fingers. A LabVIEW-based measurement software was adapted to the ALADDIN Diagnostic Device hardware for target force and feedback presentation, measurement and analysis (see General Methods).

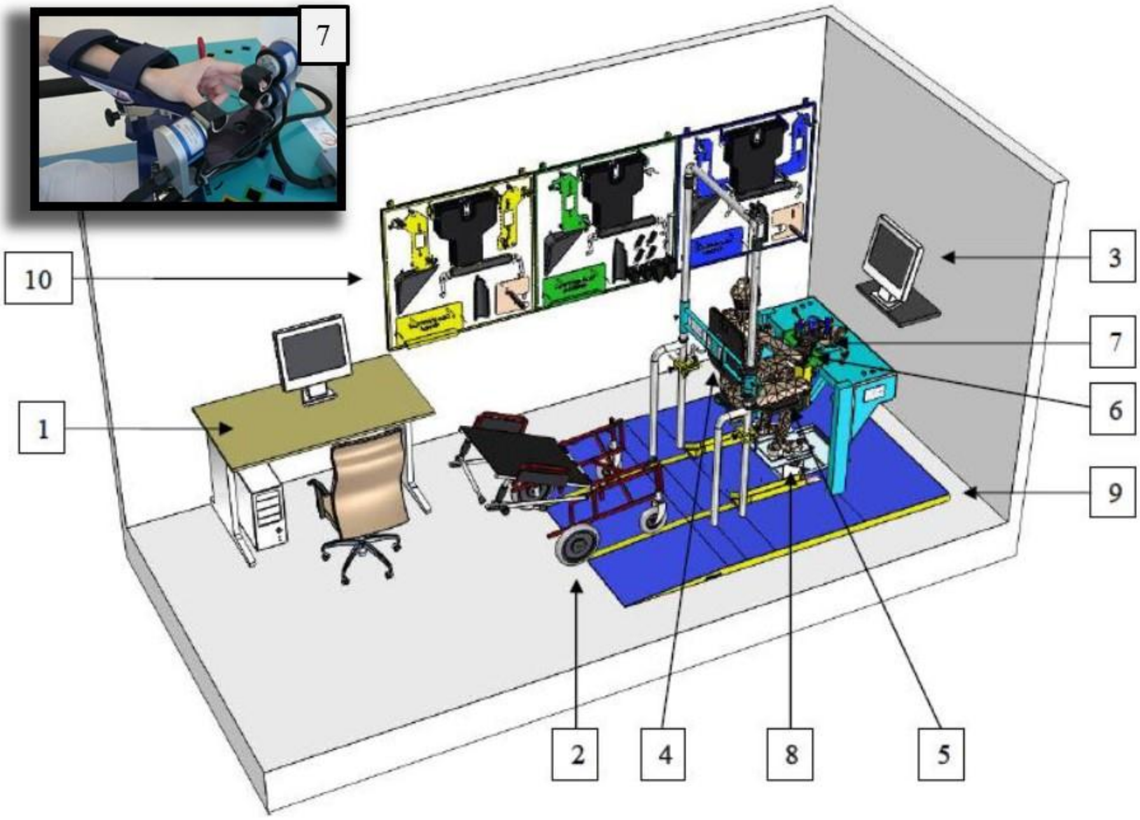

Figure 23. Apparatus in Experiment 6 was the adaptation of the ALADDIN Diagnostic Device, Van Vaerenbergh et. al. (2005). 1. Data acquisition and controller PC running LabVIEW software 2. Transit lying wheelchair 3.Monitor for the participant 4. Trunk device 5. Seat device 6. Arm device 7. Finger device 8. Foot device 9. Podium 10. Accessory storage board.

4.5.2.4 Design and procedure

Practice sessions were administered in the morning. Participants were seated, lower arm lying in an arm device (6) and fingers fit in the force sensors in front of the participants (7). A monitor showing the magnitude of target forces and feedback was mounted in eye height (3).

Before training, maximum hand grip force measurement was administered to provide target forces in maximum voluntary contraction (MVC) % of each participant.

During acquisition, both groups practiced 80 force exertions a day for four consecutive days. The constant group practiced the criterion force level (25% of MVC) while the variable group practiced five different force levels including the criterion (15, 20, 25, 30, 35% of MVC) in random order. The 80 trials were distributed into four five-minute blocks and participants had self-paced rest between them. Feedback on the exerted force level was provided following each force production. On the fifth day, a retention test (25% MVC) and a transfer test (40% MVC) was conducted. No feedback was provided in retention and transfer tests.

4.5.2.5 Dependent variable

Total error (E) was measured as dependent variable that measured both deviation from target and consistency of performance.

4.5.2.6 Data analysis

Multivariate ANOVA (group × acquisition block/retention/tansfer) was performed on total error measure by SPSS 23.0. Post-hoc analysis was performed by LSD. A p-value of 0.05 was set as significance level.

4.5.3 Results

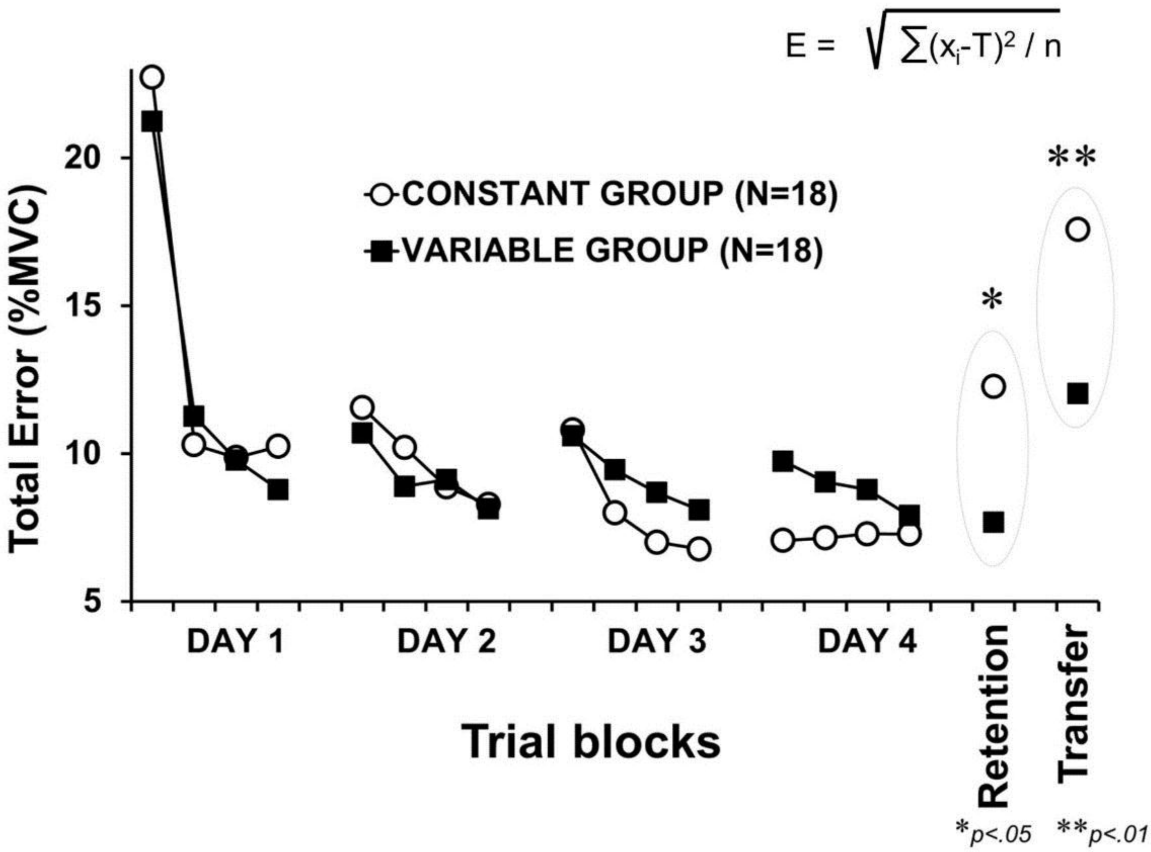

Figure 24. Mean total error (deviation and consistency) during Day 1 to Day 4 acquisition, retention and transfer tests. Performance of the two groups was similar during practice. Retention and transfer benefited from practice variability.

Multivariate ANOVA showed significant main effect for block ($F_{17, 578} = 25.14$, $p < .01$) with no significant main effect of variable/constant practice ($F_{1, 34} = 0.02$, $p > .05$).The group × block interaction was significant ($F_{17, 578} = 2.46$, $p < .01$). Multiple comparison tests revealed significantly greater absolute error in retention (F1, 34 = 4.48, $p < .05$) and transfer ($F1_{, 34} = 11.71$, $p < .01$) tests in the constant group than in the variable group. There was a significant learning effect between Day 1 and Day 5/retention ($p < .05$). Relative to the performance reached in the last block of acquisition, the constant group had lower performance in retention and both groups showed a greater level of errors in the transfer test ($p < .05$) (Fig.24.).

4.5.4 Summary of results in Experiment 6

Results showed that variable practice as well as constant practice results in learning during a four-day learning period following hemiparetic stroke. Moreover, the variable group showed superior performance during retention and transfer tests, the latter indicating generalizability of the learned skill. These results are consistent with studies of healthy participants indicating comparable learning and increased benefits for adaptation of the learned skill (Shea & Kohl, 1991; Shea et al., 2001). On the other hand, we did not find any inherent detrimental effect of variable practice on acquisition performance.

Chapter 5 DISCUSSION

The aim of the present thesis was to examine the effect of variability in practice when the participants' goal was to learn to parameterize an isometric hand grip force production task. A force production task was applied because no special attention has been paid to the effect of variability of practice hypothesis on the isometric hand grip force production even though this type of task has a great importance in daily living activities, and in both education and rehabilitation settings. There have been three main findings related to the hypotheses on variable practice schedule on motor learning. Furthermore, there was an additional finding regarding sensory threshold measurement in Experiment 3.

5.1 Variable practice is effective for learning isometric hand grip force production. Learning effect is comparable but not superior to constant practice (Experiments 1, 2 and 4).

The first hypothesis was that variable practice schedule would result in decreased performance during the acquisition session, in comparable level of skill retention and comparable or higher level of transfer performance when compared to the constant practice schedule.

The results of both Experiment 1 and Experiment 2 revealed that the groups that practiced several parameter variations of the isometric hand grip force production task during the acquisition phase (variable group) did not provide a better performance in retention and transfer tests than those groups which practiced a task with merely one parameter in the acquisition phase (constant group). This phenomenon was found in all aspects of performance examined in the experiments. That is, overall error level, bias indicating overshoot or undershoot, and consistency of performance in retention and transfer tests did not show difference in practice schedules. These results did not support the schema theory (Richard A. Schmidt, 1975) which predicted that experiencing several variations of a task during practice (variable practice) should develop a capability in the learner by which previously not practiced novel variations of the task can be produced more effectively than after constant practice.

Although the variable group did not show superior performance to the constant group in either the retention or transfer tests, the experience of several variations during acquisition may have caused an effective retention of the performance level acquired at the end of the practice. This was indicated by the lack of significant difference between the last block of acquisition and the retention test for the variable group both in AE and VE, whereas the constant group produced a significantly larger mean AE and VE in the retention test than in the last block of acquisition. This is consistent in part with the variability of practice hypothesis, although it is not as clear as reported by Shea and Kohl (1990, 1991).

As noted in the Introduction, the effect of variability of practice is often indicated as a phenomenon whereby, after committing larger errors (e.g., AE and VE) during acquisition, participants perform better on the retention and transfer test than those who receive constant practice. In the present study, this paradoxical feature of variable practice was shown in two ways. First, the variable group committed larger errors during acquisition than the constant groups. This is in line with the results of a number of previous studies (Lai & Shea, 1998; Lai et al., 2000; Proteau et al., 1994; Sekiya et al., 1994; Shea & Kohl, 1990, 1991; Sherwood, 1996). Second, the variable groups retained the performance level acquired at the end of the acquisition session, and the constant group performed significantly less well in the retention and transfer tests than at the end of the acquisition session. The advantages of variable over constant practice were therefore clearly shown in the present experiments. The variable groups easily retained their performance level acquired at the end of the acquisition period whereas the performance of the constant groups deteriorated in the retention and transfer tests in comparison with their performance at the end of the acquisition period. These findings suggest that variable practice is more effective than constant practice for the retention and transfer of an acquired force level and is therefore beneficial for the learning of the control of accurate force production.

Another important point of the present study is that there were no significant differences in the constant and variable groups in their results on the retention and transfer tests. In many previous studies, which were supportive for the effect of variability of practice (Carnahan, Van Eerd, & Allard, 1990; Catalano & Kleiner, 1984; Czyz & Moss, 2016; Marchand et al., 2017), two groups were contrasted, i.e., a less variable acquisition practice group (such as a group doing constant or blocked practice) and a more variable acquisition practice group (such as one doing a randomly scheduled practice). When these groups were compared in a retention and/or transfer test, their performances differed significantly, with the more variable acquisition groups producing smaller errors (e.g., AE) at the retention and/or transfer tests than the less variable acquisition practice groups.

In Experiments 1 and 2, the variable groups did not show smaller errors at the retention and transfer tests than the constant group. We can interpret this phenomenon in terms of task difficulty and familiarity as shown in the following way. The learning curves of both the variable and the constant groups during acquisition showed that both groups improved their performance in a quite early phase of the practice and maintained it until the end of the acquisition session. This may probably have caused a likely ceiling/floor effect; thus, the performance level was then invariable in further acquisition trials. Therefore, a likely explanation for the lack of differences between the variable and constant groups regarding errors (AE and VE) during the retention and transfer tests is that the variable group reached its performance maximum during the acquisition session (floor effect in the early phase of acquisition session) and was thus not able to improve further and become superior during the retention and transfer trials. The ceiling/floor effect suggests that, with the task used in the present study, it was quite easy for participants to become proficient at accurately adjusting the force production. The hand grip action used in the present study was a simple and familiar force production action. Furthermore, the relatively low magnitude of the target forces and the range spanned by the target forces applied might also have been familiar to the participants suggesting that the schema theory may not predict the result for a highly familiar and easy task.

Similarly, Pease and Rupnow (1983) used a task in which child participants exerted different force levels by moving a toy car along a track. This task may have been familiar to the child participants and therefore did not produce superior learning of a variable practice group compared to a constant practice group. On the contrary, Shea and Kohl (1990, 1991) applied a task not often used in everyday activities. Their unusual task resulted in a significant difference between the variable and constant groups in the retention tests with the variable group performing better. Tsutsui and Awaki (1991) used a task similar to the task used by Shea and Kohl, but did not find the beneficial effect of variable practice. Tsutsui and Awaki applied only a total of 21 practice trials during acquisition. Therefore, the lacking effect of variable practice may not have been due to the nature of the experimental task rather because of the small amount of practice in the acquisition phase. These findings suggested that whether the effect of variability of practice arises in a force production task may depend on the nature, such as the difficulty and/or familiarity, of the task to be learned as well as the amount of practice or interactions between both. **In answer to my first hypothesis, results provide partial support: while lower performance was characteristic during the learning of isometric force production, a beneficial effect was present only in terms of retention of the skill but not in superior performance.**

In order to pursue the problem further, task difficulty had to be addressed. Since grip force production was in the focus of the study, task difficulty should have been increased without changing the nature of the task significantly. A possible solution was to increase task difficulty in terms of increasing the difficulty of discrimination between different target force levels in the variable group. In order to define appropriate target force levels in the following experiment, a novel method for the measurement of isometric force discrimination was elaborated in Experiment 3. My hypothesis was that the discrimination threshold for isometric force production would be similar or higher than in isotonic force production tasks. **Results confirmed the second hypothesis on sensory discrimination threshold level, namely that the threshold for isometric force production was higher than previously found in isotonic force production tasks.** Characterisation of the discrimination threshold allowed the application of target forces with a difference below the threshold between the target forces in Experiment 4.

In Experiment 4, the effect of variability of practice was studied using an isometric hand grip force production task with force level differences below the discrimination threshold gained in Experiment 3. My hypothesis was that increasing difficulty in the means of decreased inter-target difference but keeping the number of task variations invariable may result in improved performance in terms of retention and transfer in the variable practice group. The main finding of Experiment 4 was that decreasing variability in terms of decreased difference between targets below threshold and decreased range of target forces resulted in diminished difference between variable and constant groups in all aspects of the motor task, such as overall error level and consistency. This phenomenon was found both during the learning phase and the testing phase of retention and transfer. **These findings do not support my third hypothesis that increased task difficulty in terms of discrimination between target force levels results in improved retention and transfer performance**. On the contrary, the decreased range of parameters resulted in the same performance pattern as the constant practice schedule. Here, the number of task variants did not differ from previous experiments in the variable group. Only the reduced range of target forces and the reduced difference between target force levels resulted in a performance very close to that of the constant group. Furthermore, the results of Experiments 1,2 and 4 suggest that the range of parameters practiced during acquisition may influence performance during acquisition, e.g., lower range in Experiment 4 resulted in lower levels of errors during acquisition. While no studies addressed parameter learning in terms of range of target forces up to date, Ranganathan and Newell (2010) examined the effect of range of parameters in an obstacle crossing task. Here, three groups of participants practiced with low variability (only the target), medium variability (target±1 cm) and high variability (target±2cm), respectively. On the retention and transfer tests, the group practicing only the target task showed the most accurate performance both on the target task and in the task of high variability. Authors concluded that low variability practice (only on target) allows for the learning of a particular task-relevant parameter on target location that ensures the lowest variability and effective adaptation. While the nature of the task was different in the experiment of Ranganathan and Newell (2010), results are contradictory to our results in terms of learning effect.

In conclusion, the results of the present studies (Experiment 1, 2 and 4) indicated that variable practice may be good for the retention for at least 24 hours of a constant performance level acquired at the end of a practice session, whereas constant practice may result in deterioration. This is partially consistent with the variability of practice hypothesis, although the two groups did not significantly differ in the absolute performance level for retention and transfer. Furthermore, the necessity for investigating the effect of the range of parameters practiced during acquisition arose.

5.2 Variability in terms of inter-target difference and range of practiced parameters affects both performance during acquisition and retention and transfer ability.

In experiment 5, the influence of parameter range on acquisition, retention and transfer was studied during learning isometric hand grip. My hypothesis was that if the schema theory holds, increased variability with a broader range of force production levels experienced in practice would be advantageous in subsequent retention and transfer tests. The results showed that the range of experienced force levels during practice generally determined the amount of errors during practice. Increasing the range size of target forces performed in practice generally increased performance errors during acquisition, which resulted in the highest variability group (i.e., variable 10%) showing the largest amount of errors in AE, VE, and E. This may probably be a general and robust nature of motor learning, which has been evident in studies dealing with experimental manipulations of either introducing more variations from a certain class movement or scheduling practice tasks in random/serial order compared to blocked practice. Such a phenomenon has been evident in various types of tasks (e.g., timing), including force production (Lee et al., 1985; Shea & Kohl, 1990, 1991; Shea et al., 2001).

In contrast to the variable 10% group, the other three groups (the constant and the variable 2.5% and 5% groups) that practiced the force production task with relatively lower variability (with or less than 5% MVC between target forces) generally resulted in nonsignificant differences in VE, CE, AE or E. Although these three groups differed in the range of force levels experienced during practice, they produced similar amounts of errors during practice. A possible explanation for the lack of difference in performance errors during practice is that relatively lower variability in practicing a target force results in a similar performance in the amounts of error. King & Newell, 2013 have recently found that time scales of isometric force production with the hand does not show any apparent differences between the constant and variable practice schedules regarding error level when practicing a force production task in a range of 15 and 25% MVC. It is therefore suggested that the range of experienced parameters affects error level during acquisition with a wide range of parameters resulting in a considerably higher level of errors under variable practice conditions.

The present results indicated that the variability manipulated by differing the range of force levels during practice did not have a significant influence on recalling the criterion task since there was no significant difference between practice groups in the retention test after one day. Furthermore, the group with the highest variability (variable 10% group) that performed with the largest errors during acquisition did not outperform other groups in the retention test. Contrary to our results, Shea and Kohl (1990, 1991) found the variable practice schedule advantageous compared to constant practice for the retention of isometric force production with the elbow extensors. On the other hand, our results are consistent with the findings of King and Newell (2013) who did not find difference between constant and variable schedules during the retention test using force production time series with the hand.

Regarding the transfer test, the groups practicing with the lowest variability (the constant and variable 2.5% groups) showed the poorest performance. Although the variable 5% group experienced a higher variability but resulted in a similar amount of errors to the constant and 2.5% groups during acquisition, this group showed the most superior performance in the transfer test. Similar beneficial effect of increasing parameter variability was found in e.g., an absolute timing task regarding transfer (Shea et al., 2001). Increasing the extent of variability further during practice in the variable 10% group led to a large amount of errors during acquisition but did not produce any superior performance in the transfer test. Therefore, relatively a high variability with a less amount of errors during acquisition as in the variable 5% group promoted the transfer to a new force production the best.

These findings partially support my hypothesis based on the schema theory: increasing the range of parameters during learning led to superior performance when a novel variation of motor action had to be produced. On the other hand, increasing variability above a certain level did not give a further rise to transfer performance. The variability of practice hypothesis predicts that practicing a certain variation within a class of movement has a beneficial effect on learning but does not give a prediction on the size of the interval that practice parameters should include. That is, the variability of practice hypothesis of the schema theory does not take into consideration the range covered by the practised parameters and the range that would be advantageous for learning (Schmidt, 1975). The present results indicate that experiencing a moderate variability (i.e., variable 5% group) within a class of movement/force production is effective for producing a novel force level, whereas experiencing excessive variability above a certain level (variable 10% group) does not have additional benefits. This suggests that there should be an optimum range of parameters within variable practice that promotes learning the best.

5.3 Variable practice is effective for learning isometric hand grip after stroke.

Practice variability in learning accurate hand grip after stoke was studied in Experiment 6. My hypothesis was that the characteristics of variable practice as compared to constant practice e.g., higher error level during practice, but successful or more effective learning in terms of retention and transfer would be present after hemiparetic stroke. This study showed that variable practice as well as constant practice results in learning during a four-day learning period. Moreover, the variable group showed superior performance during retention and transfer tests, the latter indicating the generalizability of the learned skill. These results are consistent with studies of healthy participants indicating comparable learning and increased benefits for adaptation of the learned skill (Shea & Kohl, 1991; Shea et al., 2001). A recent study of Rhea et al. (2012) also reported the beneficial effect of variable practice after stroke. Here, participants underwent a two-session gait training. One subgroup practiced with constant and another subgroup with variable treadmill speed. Those participants who trained under variable condition achieved a more regular pattern of knee movements during gait, highlighting the advantage of training with practice variability after stroke.

In our study, however, the detrimental effect of variable practice on acquisition performance was not present as seen in Experiments 1-5. The performance of the variable group did not differ from the constant group in acquisition. A possible explanation is that feedback during training may have guided performance and reduced error level (Lee et al., 2015). An increasing error level in both groups at learning tests when feedback was not present supports this assumption. This phenomenon has also been previously described in studies focusing on the effect of feedback on performance (Ranganathan & Newell, 2009; Sigrist, Rauter, Riener, & Wolf, 2013). When comparing results of Experiment 6 to that of learning Experiments 1, 2, 4 and 5 some methodological differences should be noted. Participants of Experiment 1-5. were healthy young adults who practiced for a one-day-session. In contrast, participants of Experiment 6 were older adults with hemiparesis whose practice was distributed into 4 training days to avoid undesirable effect of fatigue on performance. The differences in age, distribution and the presence of neurological condition likely affected performance during learning and make some limitation on the comparison of results.

To summarize, **results partially support my hypothesis: the detrimental effect of practice variability was not present but advantages in terms of superior performance in retention and transfer appeared.**

While there are numerous methods to enhance the hand function after stroke (Michielsen et al., 2011; Peter et al., 2011; Schuster-Amft et al., 2018; Wilson et al., 2016; Wu et al., 2011), our results contribute with novel evidence to a rarely investigated field of long-term learning of hand grip (Fan, Voisin, Milot, Higgins, & Boudrias, 2017; Reis et al., 2009) after stroke.

5.4 Limitations and further research

The studies in this thesis have several limitations. Age range of the healthy study population covered young adults, but the effect of variability during practice may have differential effect due to age as previous research suggested (Dick et al., 2000; Pease & Rupnow, 1983). A broader age span including both youngsters and elderly individuals is necessary for increasing the impact of the results.

Furthermore, the design in Experiments 1, 2, 4 and 5 allowed the study of short term learning which is the fast initial phase of motor learning. Further studies need to clarify if similar a learning pattern can be found after longer acquisition periods (e.g., days, weeks). More importantly, follow-up is desirable to evaluate on the long term effects of learning both in healthy population and in stroke survivors. Changing variability level (constant, blocked, random practice) during the course of learning in different phases of learning also remains to be explored both in typical and atypical development. A recent study suggests that increasing variability of movements is likely beneficial in atypical development where a limited motor repertoire is experienced during development (Hadders-Algra, 2010). These propositions, however, remain to be further investigated.

Although it was not a focus of the present thesis the relationship and generalizability of motor learning from simple tasks such as the one used in the present thesis to functional abilities should be further revealed. As shown in the introduction section, the hand has a complex sensorimotor function. Mapping motor learning capacity as a function of sensory and functional status could add to our understanding of sensorimotor recovery after stroke or in atypical development. Since proprioception plays an essential role in hand grip, its function needs to be addressed. This could be carried out by the novel discrimination threshold measurement method developed in this thesis. This method is applicable for characterizing the just-noticeable difference level during isometric hand grip force production with one hand at a time. Adaptation of the method for conditions after central nervous system damage would provide a well-measurable proprioceptive function not yet used in the field of neurorehabilitation.

Chapter 6 SUMMARY AND CONCLUSIONS

The aim of the present thesis was to study the effect of practice variability on the acquisition of accurate isometric hand grip force production, a component that plays a crucial role both in fine and gross motor functions of the hand. There are three main findings of the thesis regarding learning in young adults and adult stroke survivors.

1. Introducing variability to the learned parameters during acquisition led to higher level of errors during the learning phase compared to a group that practiced only the target force. This phenomenon was present both in overall accuracy and consistency of the performance. As to the means of retention of the learned skill, the two types of practice resulted in the same skill level in all aspects of performance 24 hours after acquisition. A marked difference between the variable and the constant schedule was that those who practiced under the variable condition were able to retain the level of performance achieved by the end of the practice while the level of performance of those who practiced under the constant schedule declined (Vámos & Imanaka, 2007).
2. A novel finding to the field was that the range of parameters applied in variable condition practice schedule determined the error level in the learning phase and affected retention and transfer performance as well. Increasing the range of parameters by increasing inter-target difference resulted in a higher level of errors during acquisition. Higher variability, however, was beneficial for learning only within a certain range of practiced parameters. Larger range does not promote better performance during acquisition and learning tests above a given level. It indicates the existence

of an optimum range of parameters for a given target to be learned (Vámos & Imanaka, 2015).

3. Variable practice schedule was advantageous for learning hand grip after stroke. In hemiparetic stroke survivors, learning showed a pattern different from that of healthy adults. Here, variability did not lead to decreased performance during a long term learning phase but redounded to superior performance in the retention and transfer of the learned skill showing a clear advantage compared to the constant practice group (Vamos, Berencsi, Fazekas, & Kullmann, 2018).

Taken together, variable practice schedule was proven to be beneficial for learning isometric hand grip force production both in healthy population and after central nervous system damage in hemiparetic stroke patients.

As the present thesis and previous research confirmed, variable practice could be beneficial in motor rehabilitation programmes. It could suit physical therapy sessions during gait training or hydrotherapy exercises. Furthermore, occupational therapy training sessions may benefit from variable training schedule when practicing activities of daily living. In education, variable practice could provide diversity and an enriched learning environment not only physical education classes but also classes that require fine motor function of the hand such as writing, handicraft or learning to play a musical instrument.

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