Das Erlernen räumlicher und dynamischer Bewegungsmerkmale mit Roboterunterstützung

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Zusammenfassung

Haptische Demonstration ist eine gängige Methode im therapeutischen sowie sport-, musik- und arbeitswissenschaftlichen Kontext, um motorische Fertigkeiten zu trainieren. Dabei versucht ein Trainer einem Schüler eine Bewegung beizubringen, indem er ihn physisch durch diese führt. Seit einigen Jahren gibt es Bestrebungen, Roboter zu entwickeln, welche den Schüler führen und somit menschliche Therapeuten und Trainer unterstützen und ersetzen können. Verschiedenste Roboter wurden bisher entwickelt, um Bewegungen der oberen Extremitäten sowie Laufbewegungen zu unterstützen, und eine Vielzahl experimenteller Studien wurde durchgeführt, um deren Wirksamkeit zu untersuchen. Die Ergebnisse dieser Studien sind jedoch sehr ambivalent: Bis heute ist unklar, ob ein haptisches Robotertraining Bewegungslernen fördern kann und welche Vorteile es gegenüber anderen Trainingsmethoden bietet. Die Ergebnisse einiger Untersuchungen liefern allerdings erste Hinweise darauf, dass möglicherweise dynamische Aspekte wie Timing oder Geschwindigkeit besonders von einem solchen Training profitieren. Ziel der vorgestellten Arbeiten war es daher, den Einfluss einer Roboterunterstützung auf das Erlernen von räumlichen und dynamischen Aspekten bei verschiedenen motorischen Aufgaben differenzierter zu untersuchen.

Zur experimentellen Bearbeitung der Fragestellung wurden drei Studien durchgeführt, bei welchen die Probanden verschiedene feinmotorische Bewegungen erlernen sollten. Die Leistung von Experimentalprobanden, welche in einer Lernphase von einem Roboter unterstützt wurden, wurde jeweils mit der Leistung von Kontrollprobanden verglichen. Studie 1, in welcher die Probanden lernen sollten, eine Zeichenbewegung mit einem unnatürlichen Geschwindigkeitsprofil auszuführen, konnte keine eindeutigen Ergebnisse bezüglich der Effektivität des Robotertrainings liefern. Nach Abschalten der Roboterunterstützung unterschieden sich die Gruppen zwar in Bezug auf das dynamische Merkmal Geschwindigkeitsmodulation, die Ergebnisse legten jedoch nahe, dass dies aufgrund von Sekundäreffekten zu Stande gekommen ist. In Studie 2 wurde der Einfluss eines Robotertrainings auf verschiedene Arten motorischen Timings untersucht. Es zeigte sich, dass das Erlernen von relativem Ti-

ming besonders von der Roboterunterstützung profitiert. Studie 3 konnte zeigen, dass eine haptische Demonstration förderlich für das Erlernen des Geschwindigkeitsprofils der Bewegung ist, wogegen visuelle Demonstration besser für das Erlernen der räumlichen Bewegungsaspekte geeignet ist.

Zusammenfassend unterstützen die Ergebnisse der drei Studien die Hypothese, dass ein haptisches Robotertraining für das Erlernen dynamischer Bewegungsaspekte geeignet ist, wogegen räumliche Merkmale weniger von dieser Art des Trainings profitieren.

Abstract

Haptic guidance, where the teacher demonstrates a desired movement to the student by moving his limb, is a common technique for motor skill training of impaired and healthy persons. There is an increasing interest in developing robotic devices for haptic guidance and thereby making motor skill training more efficient. Various robots have been developed to support movements of the upper limbs and gait, and many studies have been conducted to evaluate their effects on motor learning. The results of these studies are quite ambiguous. The question whether robotic guidance can facilitate motor learning and is superior to other training protocols is not answered yet. However, there is tentative evidence that the learning of dynamic movement characteristics, such as timing and velocity, might profit in particular from robotic guidance training. The purpose of the present studies was therefore to further investigate the effects of such training on the learning of dynamic and spatial aspects in different motor tasks.

Three studies in which participants learned to perform different motor tasks were conducted. In each case the performance of an experimental group, who was supported by a robot in a learning phase, was compared to the performance of a control group without guidance during learning. The results of Study 1, in which participants had to learn to make a movement with an unnatural velocity profile, did not provide clear evidence as to the effects of the robot training. After the guidance had been removed, experimental participants were still more accurate in the dynamic measure of velocity profile amplitude, but the results suggest that this was due to secondary effects of the task. In Study 2 the effects of robotic guidance on different kinds of motor timing were investigated. It could be shown that the learning of relative timing benefits in particular from the robot training. Study 3 proved that haptic guidance is superior for the learning of the velocity profile of the movement, whereas visual demonstration is better for the learning of spatial aspects. Taken together, the results of the three studies confirm the hypothesis that robotic guidance training can support the learning of dynamic, but not of spatial movement characteristics.

1 Einleitung

Das Erlernen motorischer Fertigkeiten und die Auge-Hand-Koordination gehört zu den wesentlichen Herausforderungen im alltäglichen Leben. Verschiedenste Trainingsmethoden wurden daher entwickelt, um Bewegungslernen im therapeutischen sowie sport-, musik- und arbeitswissenschaftlichen Kontext möglichst effizient und effektiv zu gestalten. Haptische Demonstration ist eine dieser Trainingmöglichkeiten. Dabei besteht ein direkter mechanischer Kontakt zwischen einem Therapeuten oder Trainer und einem Patienten oder Schüler und ersterer demonstriert die Bewegung, indem er letzteren physisch durch diese führt (Henmi & Yoshikawa, 1998). Haptische Demonstrationen, mit welcher ein Tennistrainer beispielsweise seinem Schüler einen Aufschlag oder der Therapeut einem Schlaganfallpatienten das Greifen nach einem Glas beizubringen versucht, sind weit verbreitet. Die rasche Entwicklung neuer Technologien bietet nun neue Möglichkeiten zur Gestaltung haptischen Trainings. So lassen sich robotische Geräte dazu nutzen, um Bewegungslernen zu verbessern (Reinkensmeyer & Patton, 2009). Bei einem haptischen Robotertraining übernimmt ein Roboter die Aufgabe des Therapeuten beziehungsweise Trainers und demonstriert die jeweilige Bewegung, indem er den Schüler mit den entsprechenden Bewegungsdynamiken entlang einer bestimmten Trajektorie führt.

Verschiedenste robotische Geräte wurden bisher entwickelt, um Bewegungslernen zu unterstützen (siehe Marchal-Crespo & Reinkensmeyer, 2009 zur Übersicht). Bis heute ist die Effizienz dieser Trainingsmethode jedoch nicht eindeutig belegt. Ziel der vorliegenden Arbeiten war es daher, anhand zweidimensionaler feinmotorischer Zeichenbewegungen zu untersuchen, ob ein haptisches Robotertraining das Erlernen räumlicher und/oder dynamischer Bewegungsmerkmale fördern kann.

1.1 Theoretischer Hintergrund

Neben dem visuellen Eindruck spielt beim Erlernen motorischer Fertigkeiten die Propriozeption eine zentrale Rolle (Ghez, Gordon, Ghilardi & Christakos, 1995; Ghez, Gordon, Ghilardi, Christakos & Cooper, 1990; Gordon, Ghilardi & Ghez, 1995; Sainburg, Ghilardi, Poizner & Ghez, 1995). Propriozeption beschreibt die Wahrnehmung der Lage (Positionssinn) und Bewegung (Kinästhesie) der eigenen Gliedmaßen im Raum (Schmidt, 1998). Sie führt zusammen mit der taktilen Wahrnehmung, der Temperaturwahrnehmung und der Nozizeption zu einem haptischen Sinneseindruck. Wird eine Bewegung rein visuell demonstriert, so erhält der Schüler Informationen, welche in einem visuell-räumlichen Koordinatensystem repräsentiert sind. Wenn die Bewegung nun nachgeahmt werden soll, müssen diese Informationen zunächst in ein kinematisch-propriozeptives Koordinatensystem übersetzt werden, um die Kräfte der Muskeln und die Lage der Gelenke zu spezifizieren (Desmurget, Pelisson, Rossetti & Prablanc, 1998; Feygin, Keehner & Tendick, 2002; Grindlay, 2008; Krakauer, Ghilardi & Ghez, 1999; Lee & Choi, 2010). Dies kann mitunter zu Schwierigkeiten führen. Gelingt die Übersetzung nicht, wird der Schüler keine korrekte propriozeptive Rückmeldung erhalten, d. h. er wird nicht erfahren, wie sich die richtige Bewegung „anfühlt". Bewegungslernen kann somit erschwert sein. Eine haptische Demonstration dagegen ermöglicht dem Schüler, die korrekte Bewegung nicht nur visuell wahrzunehmen, sondern auch propriozeptiv zu erfahren.

Traditionell erfolgt die haptische Demonstration durch einen Therapeuten oder Lehrer, indem dieser mit seiner Hand das entsprechende Körperglied des Patienten oder Schülers führt. Ist ein Objekt Teil der zu erlernenden Bewegung, so gibt es laut Gillespie, O'Modhrain, Tang, Zaretzky und Pham (1998) drei verschiedene Kontaktparadigmen, welche sich darin unterscheiden, wie der Kontakt zwischen Trainer, Schüler und Objekt arrangiert ist. Beim indirekten Paradigma existiert kein direkter Kontakt zwischen Schüler und Lehrer, sondern beide fassen das Objekt an verschieden Stellen. Der Lehrer führt das Objekt und der Schüler soll die Bewegung zu einem späteren Zeitpunkt reproduzieren. Da dieser jedoch während der Demonstration sowohl die Dynamiken des Objektes als auch die des Lehrers spürt, kann es ihm schwer fallen, diese zu trennen und somit Implikationen für das eigene Verhalten abzuleiten. Dem entgegen stehen zwei direkte Kontaktparadigmen. Beim einfachen direkten Kontaktparadigma legt der Schüler seine Hand auf die des Lehrers, während dieser das Objekt manipuliert. Dabei kann der Schüler die Handlung des Lehrers und gleichzeitig die Dynamiken des Objektes erleben. Da die Objektdynamiken jedoch durch die Hand des Lehrers gefiltert werden, sind diese nur spürbar, wenn die mechanische Impedanz des Objektes nicht zu gering im Vergleich zu der der Hand des Lehrers ausfällt. Beim doppelten Kontaktparadigma schließlich greift der Lehrer die Hand des Schülers, welche wiederum das Objekt hält. Somit hat der Schüler zwei Kontakte und spürt gleichzeitig die Aktionen des Lehrers sowie die Reaktionen des Objektes, welche getrennt attribuiert werden können.

In jedem dieser drei Fälle kann die Interaktion anstatt mit einem menschlichen auch mit einem robotischen Trainer erfolgen. Dabei können die Kräfte beispielsweise auch direkt über das betreffende Objekt, z. B. einen Schläger oder Stift, übertragen werden. Der Schüler oder Patient kann dieses Objekt greifen und von diesem geführt werden. Diese Substitution durch einen Roboter bietet einige Vor-, aber auch Nachteile, welche in den folgenden zwei Abschnitten gemeinsam mit den Vor- und Nachteilen haptischer Trainings im Allgemeinen ausführlicher diskutiert werden.

1.1.1 Vorteile haptischer Robotertrainings

Verschiedene Studien (Blandin, Lhuisset & Proteau, 1999; Laguna, 2000) konnten zeigen, dass motorisches Lernen verbessert werden kann, wenn die Probanden zusätzlich zu einer visuellen Demonstration der Bewegung die Gelegenheit erhalten, diese praktisch auszuführen und somit haptisch zu erfahren. Bei sehr komplexen Bewegungen kann die Produktion der korrekten Bewegung anfänglich jedoch schwierig sein. Wie einleitend bereits erwähnt, liegt der größte Vorteil eines haptischen Trainings somit darin, dass es dem Schüler oder Patienten ermöglicht, die korrekte Bewegung von Anfang an korrekt zu erleben, nachzufühlen und daraus Schlüsse zu ziehen, wie die Bewegung repliziert werden kann (Liu, Cramer & Reinkensmeyer, 2006; Reinkensmeyer & Patton, 2009). Zudem kann durch das haptische Training somatosensorische Stimulation und kortikale Plastizität gefördert werden (Carel, Loubinoux, Boulanouar, Manelfe, Rascol, Celsis & Cholet, 2000; Weiller, Jueptner, Fellows, Rijntjes, Leonhardt, Kiebel, Müller, Diener & Thilmann, 1996). Fitts (1964) unterscheidet beim Erlernen motorischer Fertigkeiten drei Phasen: In der kognitiven Phase entwickelt der Lernende zunächst ein Verständnis der Aufgabe. Die

Bewegung wird bewusst verbal repräsentiert. In der exekutiven Phase wird dann eine Methode ausgewählt, mit welcher die Aufgabe gelöst werden soll. Einzelne Bewegungskomponenten werden entsprechend ihrer Wirksamkeit evaluiert und gegebenenfalls modifiziert. In der autonomen Phase schließlich ist keine bewusste Kontrolle, beispielsweise in Form von Verbalisierungen, mehr nötig. Ein haptisches Training soll das motorische Lernen vor allem innerhalb der ersten beiden dieser drei Phasen fördern können (Feygin et al., 2002). Dabei trägt es in der ersten Phase dazu bei, die Aufgabe zu demonstrieren und verbale Instruktionen mit motorischen Anforderungen zu verknüpfen. In der assoziativen Phase werden konkrete Bewegungen gezeigt, mit welchen die Aufgabenanforderungen gelöst werden können.

Ein großer Vorteil haptischer Trainings liegt darin, dass diese nicht auf visuelle Wahrnehmung angewiesen sind. Dies eröffnet nicht nur neue Trainingsmöglichkeiten für visuell beeinträchtigte Personen, sondern ist auch besonders hilfreich für das Trainieren solcher Bewegungen, welche ein koordiniertes Zusammenwirken verschiedener Gelenke erfordern, während der Blick auf Objekte außerhalb des Körpers gerichtet ist, z. B. beim Erlernen von Ballsportarten (Reinkensmeyer & Patton, 2009). Allgemein kann haptische Führung dazu beitragen, Aufmerksamkeitsressourcen frei zu machen (Palluel-Germain, Bara, Hillairet de Boisferon, Hennion, Gouagout & Gentaz, 2007), was zum einen beim Training von Personen mit Aufmerksamkeitsstörungen nützlich ist, aber auch beim Erlernen sehr komplexer Bewegungen hilfreich sein kann. Bestimmte Bewegungskomponenten können somit geführt werden, während das Augenmerk auf die Perfektionierung anderer Komponenten gelegt werden kann (Reinkensmeyer & Patton, 2009).

Haptische Führung verhindert große Bewegungsfehler. Dies macht das Training zum einen sicherer (Huegel & O'Malley, 2010; Marchal-Crespo & Reinkensmeyer, 2008a; Schmidt & Lee, 1999), vor allem wenn es um Bewegungslernen von z. B. Laufbewegungen bei stark beeinträchtigten Personen geht, für welche anderenfalls das Risiko eines Sturzes o. ä. bestehen würde. Zum anderen können laut Sanger (2004) zu große Fehler zu Beginn des Trainings Lernen verhindern, sodass es sinnvoll sein kann, Fehler, zumindest anfänglich, zu unterbinden.

Im Vergleich zu humanen Trainern bieten Roboter einige ganz pragmatische Vorteile: Ein robotischer Trainer kann, ebenso wie menschliche Trainer und Therapeuten, die Leistung des Schülers ständig registrieren und bewerten und darauf aufbauend Rückmeldung geben und mit diesem interagieren. Im Vergleich zu menschlichen Trainern sind Roboter dabei jedoch weitaus genauer und konsistenter, d. h. während menschliche Bewegungen einer gewissen Variabilität unterliegen, sind Roboter dazu in der Lage, eine Bewegung immer in exakt der gleichen Weise zu demonstrieren (Solis, Avizzano & Bergamasco, 2002). Dabei unterliegen sie keiner Ermüdung, die Demonstration kann beliebig oft wiederholt werden und Lernfortschritte können numerisch registriert werden. Roboter sind zudem weniger arbeitsintensiv und auf lange Sicht auch kostengünstiger als humane Trainer (Liu et al., 2006; Marchal-Crespo, Furumasu & Reinkensmeyer, 2010).

Die Auswahl der konkreten Bewegungsbahn und Dynamik, welche der Roboter demonstrieren soll, kann nach verschiedenen Methoden erfolgen. Neben der willkürlichen Bestimmung der Bewegungstrajektorie und der Dynamiken, welche dem Roboter übergeben werden, ist eine weitere Möglichkeit die sogenannte „record-and-play“ Strategie (z. B. Yokokohji, Hollis, Kanade, Henmi & Yoshikawa, 1996; Henmi & Yoshikawa, 1998; Srimathveeravalli & Thenkurussi, 2005). Dabei wird die Bewegung eines Experten zunächst mit Hilfe eines robotischen Gerätes aufgezeichnet und später für den Schüler abgespielt. Vorteil dieser Methode ist, dass die natürliche Bewegung eines menschlichen Experten demonstriert wird, Lehrer und Schüler jedoch räumlich sowie zeitlich voneinander unabhängig sind (Hemni & Yoshikawa, 1998; Solis et al., 2002; Teo, Burdet & Lim, 2002). Die Bewegung des Lehrers kann zudem flexibel in Bezug auf Parameter wie Geschwindigkeit, Kraft und Skalierung modifiziert und somit an die individuellen Anforderungen des Schülers bezüglich Körpergröße, Kraft und Fertigkeitslevel angepasst werden (Hemni & Yoshikawa, 1998; Teo et al., 2002). Eine weitere Möglichkeit für die Modellierung der gewählten Bewegung bieten Computermodelle motorischen Lernens, auf deren Basis die passenden Kräfte bestimmt werden können (Reinkensmeyer & Patton, 2009).

Abschließend sei auf die psychologische Komponente eines haptischen Robotertrainings hingewiesen. Da mit Hilfe des Roboters die korrekte Bewegung unmittelbar ausgeführt werden kann, empfinden gerade Patienten mit starken Beeinträchtigungen dieses Training als weniger entmutigend und frustrierend als herkömmliche Trainings, bei welchen oft hunderte vergebliche Wiederholungen absolviert werden (Marchal-Crespo & Reinkensmeyer, 2009; Reinkensmeyer & Housman, 2007; Reinkensmeyer & Patton, 2009).

1.1.2 Probleme haptischer Robotertrainings

Neben den vielen Vorteilen, welche ein haptisches Training bietet, gibt es auch einige Zweifel an diesem Paradigma. Zwar ermöglichen haptische Trainings, wie oben beschrieben, dass der Schüler die korrekte Bewegung erlebt und propriozeptive Informationen erhält. Reinkensmeyer und Patton (2009) bemerken jedoch, dass dies nicht zwangsläufig bedeutet, dass die Informationen auch in die entsprechenden motorischen Kommandos übersetzt werden können. Während die haptische Führung per Definition zu einer besseren Leistung während des Trainings führt, bleibt somit unklar, ob die Leistung auch dann erhalten werden kann, wenn die Führung abgeschaltet wird und der Schüler die Bewegung völlig frei ausführen muss.

Die Verhinderung von Fehlern kann zudem negative Implikationen mit sich bringen. So werden Fehler in vielen Modellen als essentieller Bestandteil motorischen Lernens angesehen, auf deren Basis das Bewegungsziel mit der tatsächlichen Bewegung verglichen und anschließend eine Bewertung und Korrektur letzterer vorgenommen wird (z. B. Kawato, Furukawa & Suzuki, 1987; Schmidt, 1975). Finden nun keine Fehler statt, könnte dieser Prozess gestört werden (Reinkensmeyer & Patton, 2009). Einige Autoren (z. B. Basteris & Sanguineti, 2011; Huegel & O'Malley, 2010; Marchal-Crespo & Reinkensmeyer, 2008a; Marchal-Crespo & Reinkensmeyer, 2009; Reinkensmeyer & Patton, 2009; Winstein, Pohl & Lewthwaite, 1994) weisen zudem darauf hin, dass durch die haptische Führung die Aufgaben- und Bewegungsdynamiken verändert werden können und somit die Dynamiken während des Trainings nicht identisch mit denen der realen Aufgabe sind, was Bewegungslernen erschweren kann.

Ein weiteres großes Problem bei haptischen Trainings wird häufig mit dem Begriff „Slacking“ beschrieben (Marchal-Crespo & Reinkensmeyer, 2009). Dieses meint die Tendenz der Schüler, nachlässig zu werden, sobald sie merken, dass ihre Bewegung, unabhängig ihrer eigenen Leistung, vom Roboter unterstützt wird. Eine Abnahme in der Anstrengung, Aufmerksamkeit und Motivation kann die Folge sein. Somit entwickelt sich eine Art Abhängigkeit (ähnlich wie zuvor schon bei verschiedenen Arten von Rückmeldung gezeigt, z. B. Ho & Shea, 1978; Winstein, Pohl, Cardinale, Green, Scholtz & Walters, 1996) von der haptischen Führung, welche dazu führt, dass die Leistung der Schüler sich verschlechtert, sobald sie die Bewegung frei ausführen sollen (Lee & Choi, 2010; Marchal-Crespo & Reinkensmeyer, 2008a; Schmidt & Bjork, 1992).

Neben den generellen Nachteilen haptischer Trainings kann auch die Substitution menschlicher Trainer oder Therapeuten durch robotische Geräte problematisch sein. Laut Schmidts Schema-Theorie des motorischen Lernens entwickeln Menschen auf Basis ihrer bisherigen Erfahrungen Regeln über ihr motorisches Verhalten (sogenannte Schemata) in Form von Parameter-Wirkungsbeziehungen (Schmidt, 1975). Je mehr Erfahrungen eine Person macht, desto genauer kann demnach die Regel für ein zukünftiges Verhalten bestimmt werden. Verschiedene Studien konnten die aus dieser Theorie abgeleitete Vorhersage, dass variable Trainingsbedingungen effektiver für das Erlernen einer Regel sind als konstante Bedingungen, bestätigen (z. B. Lee, Magill & Weeks, 1985; Shapiro & Schmidt, 1982; Shea & Kohl, 1991). Vor diesem Hintergrund könnte die in Abschnitt 1.1.1 als Vorteil angeführte Konsistenz der Bewegung des Roboters auch nachteilig für das Bewegungslernen sein.

1.1.3 Eine offene Frage: Welche Bewegungsmerkmale profitieren von einem haptischen Robotertraining?

Eine zentrale Fragestellung in der Forschung zu haptischen Robotertrainings betrifft die Identifikation von Bewegungsmerkmalen, welche von einem solchen Training profitieren. Jede Bewegung besteht aus räumlichen sowie aus zeitlichen Merkmalen. Dabei beschreiben erstere die Form der Bewegung im Raum, wogegen letztere den zeitlichen Verlauf der Bewegung bezeichnen (Georgorpoulos, 2002). Bei der zeitlichen Koordination von Bewegungen kann zudem weiter zwischen absolutem und relativem Timing unterschieden werden (Terzuolo & Viviani, 1980; Schmidt, 1985). Dabei bezeichnet absolutes Timing die Gesamtdauer einer Bewegung, wogegen relatives Timing die verhältnismäßigen Dauern einzelner Teilbewegungen beschreibt. Laut Georgopoulos (2002) liegen räumlichen und zeitlichen Aspekten verschiedene neuronale Prozesse, möglicherweise sogar Aktivitäten in verschiedenen Hirnregionen, zu Grunde.

Bis heute ist unklar, welche dieser Aspekte von einem haptischen Robotertraining profitieren können (Reinkensmeyer, Galvez, Marchal-Crespo, Wolbrecht & Bobrow, 2007). Einige der bis dato durchgeführten Studien geben jedoch erste Hinweise darauf, dass möglicherweise das Erlernen von zeitlichen Bewegungsaspekten besonders empfänglich für die positiven Effekte eines haptischen Robotertrainings sein könnte (z. B. Feygin et al., 2002; Marchal-Crespo & Reinkensmeyer, 2008a; 2010; Milot, Marchal-Crespo, Green, Cramer & Reinkensmeyer, 2010). Zudem gibt es Untersuchungen, die zeigen, dass das Erlernen von Geschwindigkeiten von einem solchen Training profitiert (z. B. Grindlay, 2008).

Geschwindigkeit ist kein rein zeitliches Maß, sondern beinhaltet auch räumliche Aspekte. Trotzdem soll Geschwindigkeit im Folgenden bei der Betrachtung zeitlicher Maße mit einbezogen werden. Deshalb wird von nun an der zeitliche Begriff erweitert und anstelle von zeitlichen von dynamischen Merkmalen gesprochen. Mit Dynamik ist im Folgenden also nicht, wie in der Robotik oder Mechanik, die Beschreibung einer Bewegung unter Betrachtung der ursächlichen Kräfte (als Gegensatz zur Kinematik als Bewegungslehre ohne Ursachenbetrachtung) gemeint (z. B. Jordan, 1996). Vielmehr meint es die zeitliche Entstehung eines statischen, räumlichen Musters. Wir betrachten somit die entstandene Bahn einer Bewegung auf der einen (räumliche Aspekte), und die zeitlichen Abläufe, mit welchen diese zu Stande kam, auf der anderen Seite (dynamische Aspekte).

1.2 Überblick: Bisherige Untersuchungen zum haptischen Robotertraining

Ein Großteil der Studien zum Einfluss haptischer Robotertrainings auf das Erlernen motorischer Fertigkeiten konzentriert sich auf die Effekte bei neurologischen Patienten nach Schlaganfällen, Rückenmarksschädigungen oder anderen neurologischen Verletzungen. Nachdem 1997 positive Trainingseffekte mit *MIT-Manus*, einem Roboter, welcher Armbewegungen unterstützt, auf das Erlernen im Vergleich zu Standard-Rehabilitationsmaßnahmen publiziert wurden (Aisen, Krebs, Hogan, McDowell & Volpe, 1997), wuchs die Zahl der Studien zum roboterunterstützten Bewegungslernen (Reinkensmeyer et al., 2007). Verschiedenste Roboter wurden entwickelt, um Bewegungen der oberen Extremitäten (z. B. Kahn, Zygman, Rymer & Reinkensmeyer, 2006; Prange, Jannink, Groothuis-Oudshoorn, Hermens & Ijzerman, 2006; Takahashi, Der-Yeghiaian, Le, Motiwala & Cramer, 2007) oder Laufbewegungen (z. B. Banala, Kim, Agrawal &. Scholz, 2009; Emken, Benitez & Reinkensmeyer, 2007; Schmidt, 2004) zu unterstützen (siehe Marchal-Crespo & Reinkensmeyer, 2009 oder Reinkensmeyer, Emken & Cramer, 2004 zur Übersicht). Die Ergebnisse dieser Studien sind nicht eindeutig: Obwohl einige Untersuchungen positive Effekte eines haptischen Robotertrainings zeigen konnten, gab es auch viele Studien, welche keine weiteren Vorteile im Gegensatz zu konventionellen Therapiemethoden nachweisen konnten. Zudem sind die therapeutischen Vorteile, wenn vorhanden, häufig eher gering (Reinkensmeyer et al., 2007).

Neben Untersuchungen mit neurologischen Patienten wurden auch Studien durchgeführt, welche zum Ziel hatten, die Effekte eines haptischen Robotertrainings auf das motorische Lernen bei gesunden Probanden zu untersuchen. Die verwendeten, meist pragmatisch ausgewählten, Aufgaben sowie die Art der Unterstützung und der Kontrollgruppe variieren dabei sehr stark zwischen den einzelnen Untersuchungen. Daher ist es schwierig ist, sie in Gruppen zusammenzufassen. Im Folgenden werden sie einzeln beschrieben.

Eines der ersten robotischen Geräte, mit welchem Probanden eine Bewegung gleichzeitig visuell und haptisch demonstriert werden konnte, war das 1996 von Yokokohji und seinen Kollegen entwickelte *WYSIWYF*-Display („*What you can see is what you can feel*“). Dabei wurden die Kräfte eines Experten aufgezeichnet und anschließend einem Schüler präsentiert. Die Autoren führten jedoch keine experimentellen Studien durch, um die Effekte von *WYSIWYF* zu untersuchen, und eine Pilotstudie konnte keine eindeutigen Ergebnisse liefern (Yokokohji et al., 1996). Die Autoren argumentieren, dass dies an der Einfachheit der Aufgabe lag, welche darin bestand, einen Würfel auf einer geraden Oberfläche zu manipulieren.

Weitere Ansätze, robotische Geräte für ein haptisches Bewegungstraining zu entwickeln und zu testen, untersuchten den Einfluss robotischer Demonstration auf das Handschreiben. Henmi und Yoshikawa (1998) wie auch Solis et al. (2002), Teo et al. (2002) und Srimathveeravalli & Thenkkurussi (2005) entwickelten virtuelle Trainingssysteme, mit welchen die Probanden lernen sollten, ihnen bisher unbekannte Buchstaben zu zeichnen. Die Zeichenbewegung wurde jeweils über den Stift, welcher in ein robotisches Gerät eingebunden war, demonstriert. Dabei verwendeten die Autoren zum Teil positionsbasierte Führung, bei welcher der Stift jeweils entlang einer Bahn geführt wurde, und teilweise kraftbasierte Führung, bei welcher die positionsunabhängigen Kräfte eines Experten wiedergegeben wurden. Letzteres beruht auf der Annahme, dass, wenn sich die haptischen Profile zwischen Experte und Schüler ähnlich sind, sich zwangsläufig auch deren Trajektorien ähneln (Srimathveeravalli & Thenkkurussi, 2005). Zwar konnten die Autoren dieser Studien zum Teil zeigen, dass die Probanden das Zeichnen der Buchstaben mit Hilfe des Roboters erlernten, jedoch wurde in keiner dieser Untersuchungen ein valider experimenteller Vergleich mit anderen Demonstrationsmethoden, wie beispielsweise einer rein visuellen, durchgeführt. Auch zeigte sich keine eindeutige Überlegenheit einer der beiden Kontrollparadigmen, positions- oder kraftbasiert. Der Fokus dieser ingenieurswissenschaftlichen Arbeiten lag vielmehr auf der Entwicklung der robotischen Geräte, anstatt auf deren Evaluation.

Erst Palluel-Germain et al. (2006; 2007) verglichen den von ihnen entwickelten visuell-haptischen Demonstrationsroboter namens *Telemaque* mit anderen Trainingsmaßnahmen. *Telemaque* bestand aus einem robotisch gesteuerten Stift, welcher die Schreibbewegungen der Probanden führen konnte und so das Erlernen des Handschreibens bei Kindern verbessern sollte. Die Aufgabe der Probanden war es, Buchstaben verschiedener Schwierigkeitsgrade zu kopieren. Die Flüssigkeit der Handschrift wurde vor und nach einem Training mit *Telemaque* anhand der Parameter Durchschnittsgeschwindigkeit, Anzahl der Geschwindigkeitsspitzen und Anzahl der Pausen während der Buchstabenproduktion bewertet und mit der von Kontrollprobanden verglichen. Palluel-Germain et al. konnten in zwei Studien zeigen, dass das mehrwöchige visuell-haptische Training mit *Telemaque* sowohl bei Grundschul- (2006) als auch bei Kindergartenkindern (2007) zu einer flüssigeren Handschrift (höhere Durchschnittsgeschwindigkeit, weniger Geschwindigkeitsspitzen (2006; 2007) und weniger häufiges Absetzen des Stiftes (2007)) führte als das Kontrolltraining.

Bluteau, Coquillart, Payan und Gentaz (2008) untersuchten in zwei Studien den Einfluss eines kraftbasierten und eines positionsbasierten Robotertrainings auf das Erlernen zweier Trackingaufgaben (arabische/japanische Buchstaben und Ellipsen). Sie konnten zeigen, dass haptisches Training zu einer flüssigeren Bearbeitung der Aufgaben führte. Dabei stellte sich die kraftbasierte Führung als überlegen gegenüber der positionsbasierten Führung heraus. Keines der Trainings hatte dagegen Einfluss auf räumliche Aspekte der Bewegungen.

Ein weiterer früher Versuch, robotische haptische Demonstration für das Erlernen einer komplexen Bewegung zu nutzen stammt von Gillespie et al. (1998). Sie entwickelten den *Virtual Teacher,* ein Roboter, welcher die Hand von Probanden führen kann und ihnen die optimale Strategie beibringen soll, mit welcher ein sich unter einem Karren befindendes Pendel zwischen zwei Ruhezuständen in eine Bewegung versetzt werden kann. Entscheidend war dabei, dass nach einer initialen Bewegung des Karrens, welche das Pendel in Schwingung brachte, eine zweite, leichte Bewegung gemacht werden musste, um das Pendel wieder zum Stillstand zu bringen. In einer Pilotstudie mit 24 Probanden konnten die Autoren zwar zeigen, dass Probanden mit dem *Virtual Teacher* die optimale Strategie begriffen, trotzdem konnten sie keinen signifikanten Unterschied in der Lernleistung zwischen diesen und Kontrollprobanden, welche keine Unterstützung durch den Roboter erhielten, nachweisen. Gillespie et al. argumentierten, dass dies an dem hohen Schwierigkeitsgrad der Aufgabe lag, sodass Probanden, auch wenn der *Virtual Teacher* ihnen die optimale Strategie gezeigt hatte, diese nicht eigenständig umsetzen konnten.

Einen direkten Vergleich zwischen visueller und haptischer Demonstration durch einen Roboter führten Feygin und seine Kollegen (2002) durch. Die Aufgabe der Probanden in dieser Studie war es, eine komplexe dreidimensionale Bewegung zu erlernen. Diese wurde ihnen entweder visuell demonstriert, indem sie einen Roboterarm bei der Ausführung der Bewegung beobachteten, oder haptisch, indem der Roboter die Hand der Probanden entlang der Bewegungsbahn führte, während der Blick auf die Bewegung verhindert wurde. Zudem untersuchten Feygin et al. eine weitere, visuell-haptische Bedingung, bei welcher die Probanden beides, sowohl visuelle als auch haptische Demonstration, erhielten. Im Anschluss sollten die Probanden die erlernte Bewegung in zwei Testbedingungen frei reproduzieren. In der einen Bedingung erhielten sie dabei lediglich haptische Rückmeldung, während sie die Bewegung reproduzierten, d. h. sie konnten diese nicht sehen. In der anderen Bedingung fühlten und sahen sie ihre Bewegung gleichzeitig. Die Leistung der Probanden in der Testphase wurde bezüglich räumlicher Merkmale sowie eines zeitlichen Merkmals analysiert. Feygin und seine Kollegen konnten zeigen, dass sich die visuelle und die haptische Versuchsgruppe in ihrer Leistung signifikant voneinander unterschieden. Eine rein visuelle Demonstration stellte sich dabei als vorteilhaft für das Erlernen räumlicher Bewegungsmerkmale heraus, wogegen die Probanden der haptischen Demonstrationsgruppe besser in Bezug auf das zeitliche Maß waren. Des Weiteren konnten die Autoren eine Interaktion zwischen Demonstrations- und Testbedingung feststellen: Wenn visuelle Rückmeldung während der Testphase vorhanden war, verbesserte sich die räumliche Genauigkeit der visuell trainierten Gruppe, während sich die der haptisch trainierten Gruppe verschlechterte. Im Gegensatz dazu führte visuelle Rückmeldung in der Testphase zu genauerer zeitlicher Reproduktion der Bewegung in beiden Gruppen. Die Kombination von beidem, visueller und haptischer Demonstration, führte überraschenderweise zu keiner nennenswerten weiteren Verbesserung der räumlichen oder zeitlichen Genauigkeit der Bewegung. Dies ist überraschend, da man annehmen könnte, dass zwei Quellen sensorischer Information vorteilhafter für das Lernen sein könnten als nur eine.

Um dies genauer zu untersuchen, führten Liu et al. (2006) eine ähnliche Studie durch, in welcher sie die Effekte einer rein visuellen und einer visuell-haptischen Demonstrationsbedingungen auf das Erlernen einer Bewegung untersuchten. Liu et al. analysierten die Bewegungen jedoch ausschließlich in Bezug auf deren räumliche Genauigkeit. Die Ergebnisse entsprachen denen von Feygin et al. (2002): Zusätzliche hapti-sche Demonstration führte zu keiner weiteren Verbesserung der räumlichen Genauigkeit der Bewegung in der Testphase. Die Autoren argumentierten, dass visuelle Wahrnehmung möglicherweise räumlich genauer sein könnte als haptische und letztere somit zu keiner weiteren Verbesserung führt, wenn beide Formen der Rückmeldung vorhanden sind.

Neuere Untersuchungen zum haptischen Robotertraining nutzten angewandtere Aufgaben wie das Steuern eines Fahrzeuges, Flipper spielen oder Rhythmen auf einem Schlagzeug zu produzieren. Marchal-Crespo und Reinkensmeyer (2008a) entwickelten einen Rollstuhl-Lenksimulator, welcher Probanden helfen sollte, mit einem Lenkrad einen auf einem Monitor dargestellten Pfad entlang zu fahren. Sobald die Probanden falsch lenkten, wurden Kräfte auf das Lenkrad aufgeschaltet, welche den virtuellen Rollstuhl zurück auf die gewünschte Fahrbahn brachten. Entscheidend bei der Aufgabe war die Initiierung der Abbiegevorgänge. Da das Fahrzeug erst nach leichten Verzögerungen abbiegen konnte, musste schon eingelenkt werden, bevor sich die Pfadrichtung änderte. Marchal-Crespo und Reinkensmeyer konnten zeigen, dass nach dem Training robotergeführte Probanden geringere Fehler aufwiesen als Kontrollprobanden. In der roboterunterstützten Versuchsgruppe halfen die aufgeschalteten Kräfte, die Abbiegevorgänge früher zu initiieren. Die Autoren schlussfolgerten daraus, dass ein robotisches Training von Vorteil sein könnte, um das Erlernen zeitlicher Aspekte einer Aufgabe zu fördern. Marchal-Crespo und ihre Kollegen (2010) erweiterten die Ergebnisse mit einer weiteren Studie, in welcher ein realer Rollstuhl verwendet wurde, um einem auf dem Fußboden markierten Pfad zu folgen. Die Hand der Probanden konnte über den Joystick des Rollstuhles geführt werden, wenn sie von dem Pfad abwichen. Die Autoren zeigten, dass ein Training mit robotischer Führung die Lenkfertigkeit von Gesunden sowie von einem motorisch stark beeinträchtigten Kind im Vergleich zu einem Training ohne Führung verbesserte.

Der Hinweis, dass möglicherweise besonders zeitliche Aspekte von einem haptischen Robotertraining profitieren können, veranlasste Marchal-Crespo und Reinkensmeyer (2008b) des Weiteren dazu, ein Flipper-ähnliches Spiel zu verwenden, um die Effekte eines solchen Trainings auf motorisches Timing zu untersuchen. Aufgabe der Probanden war es, einen Knopf zum richtigen Zeitpunkt zu drücken, um damit eine herunterfallende Kugel auf dem Bildschirm gegen ein Zielobjekt zu stoßen. Die Hand der Probanden war dabei in einen Roboter namens *Tapper* eingespannt, welcher die Probanden darin unterstützte, im richtigen Augenblick durch eine Beugung des Handgelenks den Knopf zu drücken. Marchal-Crespo und Reinkensmeyer konnten die Hypothese, dass robotische Führung das Erlernen motorischen Timings fördert, nicht unterstützen. Die Probanden, welche mit *Tapper* trainiert hatten, waren in der Testphase nicht genauer in ihrem Timing als Kontrollprobanden, welche keine Unterstützung erfuhren. Die Autoren fanden heraus, dass sich die Probanden zu sehr auf die Unterstützung durch *Tapper* verließen und in nicht unterstützen Durchgängen schlechter waren, wenn diesen ein unterstützter Durchgang voranging. Sie argumentierten, dass dieser „Slacking-Effekt“ möglicherweise reduziert werden könne, wenn man die Probanden explizit darüber informiert, in welchen Durchgängen sie unterstützt werden und in welchen nicht.

Ein weiteres Ergebnis der Studie von Marchal-Crespo und Reinkensmeyer war eine geringere Generalisierung auf andere Zielobjekte der durch *Tapper* trainierten Probanden im Vergleich zu Kontrollpersonen. Die Autoren begründen dies mit der reduzierten Fehleranzahl und der daraus resultierenden geringeren Variabilität der Aufgabe im Training. Dem daraus entstandenen Gedanken, dass möglicherweise einer Erhöhung der erlebten Fehler zu verbessertem Lernen im Vergleich zu einem Führungstraining, welches Fehler reduziert, führen könne, gingen Milot et al. (2010) ein Jahr später in einer Studie nach. Dabei verglichen sie die Effekte dieser beiden Trainings auf das Erlernen der oben beschriebenen Flipperaufgabe. Eine Erhöhung der Fehler wurde dadurch erreicht, dass im Falle einer zu späten Bewegungsinitiierung durch den Probanden die Bewegung des Roboters *Tapper* zusätzlich verzögert wurde, wohingegen bei zu früher Initiierung durch den Probanden der Start der Bewegung durch *Tapper* noch mehr beschleunigt wurde. Eine Verringerung der Fehler wurde dagegen erreicht, indem *Tapper* im Falle einer zu späten Initiierung des Probanden die Bewegung beschleunigte und im Falle einer zu frühen Initiierung die Bewegung verzögerte. Milot et al. konnten zeigen, dass beides, sowohl eine Erhöhung als auch eine Verringerung der Fehler, die Leistung der Probanden verbesserte. Eine weitergehende Analyse der Daten, bei welcher die Probanden ihrem ursprünglichen Fertigkeitsniveau entsprechend in zwei Gruppen eingeteilt wurden, konnte ferner zeigen, dass Probanden mit einem höheren Fertigkeitsniveau eher von einem Fehler verstärkenden Training profitierten, während Probanden mit geringerem Fertigkeitsniveau bessere Leistungen nach dem robotischen Führungstraining, welches Fehler verringerte, zeigten. Auch Lee und Choi (2010) verglichen Roboterführung mit einem Fehler verstärkenden Training. Letzteres stellte sich in dieser Untersuchung als überlegen für das Erlernen einer Trackingaufgabe heraus.

Grindlay (2008) verglich haptische Demonstration nicht wie andere Autoren (z. B. Feygin et al., 2002; Liu et al., 2006) mit visueller Darbietung, sondern mit auditiver Demonstration. Er untersuchte die Effekte der beiden Trainingsmodalitäten auf das Produzieren rhythmischer Sequenzen am Schlagzeug. Die Probanden in dieser Studie hörten dabei entweder eine Aufnahme der Rhythmen oder wurden mit Hilfe eines Roboters, welcher an ihrem Handgelenk befestigt war, durch die Bewegung geführt. Um sicher zu gehen, dass letztere Probanden nur haptische und keine auditive Demonstration erhielten, trugen sie Kopfhörer, über welche Maskierungsgeräusche dargeboten wurden. In zwei weiteren Bedingungen schließlich erhielten die Probanden beides, auditive und haptische Demonstration. Grindlay untersuchte die Leistung der Probanden während einer Testphase bezüglich Timing und Geschwindigkeit der Bewegungen. Er konnte zeigen, dass haptische Demonstration beim Erlernen der Geschwindigkeit von Vorteil war. Die Kombination von auditivem und haptischem Training erwies sich zudem als vorteilhaft für das Erlernen des korrekten Timings, vor allem in einer frühen Phase des Lernens.

Zusammenfassend lässt sich festhalten, dass die Ergebnisse bezüglich der Effektivität eines haptischen Robotertrainings zwar sehr uneindeutig sind, die Studien von Feygin et al. (2002), Marchal-Crespo et al. (2008a; 2010) sowie Grindlay (2008), Bluteau et al. (2008) und Milot et al. (2010) jedoch vermuten lassen, dass möglicherweise dynamische Bewegungsaspekte wie Timing und Geschwindigkeit besonders von einem haptischen Robotertraining profitieren könnten.

1.3 Fragestellungen

Das Ziel der vorliegenden Arbeiten war es, die Effekte eines haptischen Robotertrainings auf das Erlernen räumlicher und vor allem dynamischer Merkmale verschiedener Bewegungen zu untersuchen. Dazu wurden drei Experimente mit verschiedenen Bewegungsaufgaben durchgeführt. Bei den Bewegungen handelte es sich stets um zweidimensionale Zeichenbewegungen, welche in einer Lernphase demonstriert und geübt und in einer Testphase reproduziert wurden. Die konkreten Fragestellungen der drei Studien waren wie folgt:

1) Kann ein haptisches Robotertraining das Erlernen einer Zeichenbewegung mit einem unnatürlichen Geschwindigkeitsprofil, welches dem sogenannten 2/3 Potenzgesetz widerspricht, erleichtern? In welchen Bewegungsaspekten unterscheiden sich diese Probanden von den Kontrollprobanden, welche die Aufgabe ohne haptische Unterstützung trainieren?

2) Kann ein haptisches Robotertraining das Erlernen motorischen Timings erleichtern? Gibt es unterschiedliche Effekte auf das Erlernen verschiedener Timingarten, wie emergentes und diskretes, absolutes und relatives Timing?

3) Wie wirkt sich ein haptisches Robotertraining auf das Erlernen räumlicher und dynamischer Bewegungsaspekte im Vergleich zu einer rein visuellen Demonstration aus? Welchen Vorteil bringt die Kombination beider Demonstrationsmodalitäten? Welchen Einfluss hat die Modalität der Testphase?

2 Studien

Die Autorin übernahm hauptverantwortlich die experimentelle Planung, Durchführung und Auswertung der drei Studien. Der prozentuale Anteil der Autorin an den einzelnen Studien lässt sich wie folgt beziffern:

Studie 1: Einleitung (80%), Methodik (85%), Datenerhebung (95%), Auswertung (95%), Diskussion (90%)

Studie 2: Einleitung (95%), Methodik (90%), Datenerhebung (90%), Auswertung (95%) , Diskussion (95%)

Studie 3: Einleitung (95%), Methodik (85%) , Datenerhebung (95%), Auswertung (85%), Diskussion (90%)

2.1 Studie 1: Der Einfluss eines haptischen Robotertrainings auf die Produktion räumlich-zeitlicher Muster

In Studie 1 wurde der Einfluss eines haptischen Robotertrainings auf das Erlernen einer Kreisbewegung mit einem unnatürlichen zeitlichen Muster, welches einem universalen Bewegungsgesetz (2/3 Potenzgesetz) widerspricht, untersucht. Aufgabe der Probanden war es, Kreise mit einem elliptischen Geschwindigkeitsprofil zu zeichnen. Dies erlernten sie, indem sie in einer Übungsphase eine Trackingaufgabe bearbeiteten. Dabei verfolgten sie mit einem Stift (dargestellt als Cursor auf dem Bildschirm) ein Zielobjekt, welches sich mit elliptischem Geschwindigkeitsprofil auf einer Kreisbahn auf dem Monitor bewegte (siehe Abbildung 1). Experimentalprobanden wurden während dieser Phase haptisch durch einen mit dem Stift verbundenen Roboter geführt. Kontrollprobanden bearbeiteten die Trackingaufgabe ohne Roboterunterstüzung. Im Anschluss folgte eine Testphase, in welcher alle Probanden die zuvor gelernte Bewegung frei reproduzierten. Die Bewegungen der Übungs- sowie Testphase wurden anschließend in Bezug auf Form und Geschwindigkeitsprofil analysiert. Bei letzterem wurde weiterhin zwischen Modulationstiming und Modulationsamplitude unterschieden. Es konnte gezeigt werden, dass das haptische Robotertraining während der Übungsphase zu einer besseren Leistung bezüglich aller drei Maße im Vergleich zu den Kontrollprobanden führte. In der Testphase hingegen, in der alle Probanden die Bewegung frei reproduzierten, verschwanden die Unterschiede weitestgehend. Lediglich in der Modulation des Geschwindigkeitsprofils unterschieden sich Experimental- und Kontrollprobanden weiterhin, wobei erstere genauer in der Amplitude der Modulation waren. Die Ergebnisse der ersten Studie konnten die Hypothese, dass robotische Führung das Erlernen dynamischer Bewegungsmerkmale unterstützt, nicht gänzlich unterstützen. Denkbare Gründe sind die Schwere der Aufgabe sowie die relativ kurze Trainingsdauer. Zudem scheinen Nebeneffekte des Robotertrainings dessen Einfluss auf das Erlernen der Aufgabe überlagert zu haben, sodass keine eindeutigen Schlüsse auf die Effekte eines solchen Trainings auf die verwendete Aufgabe möglich sind.

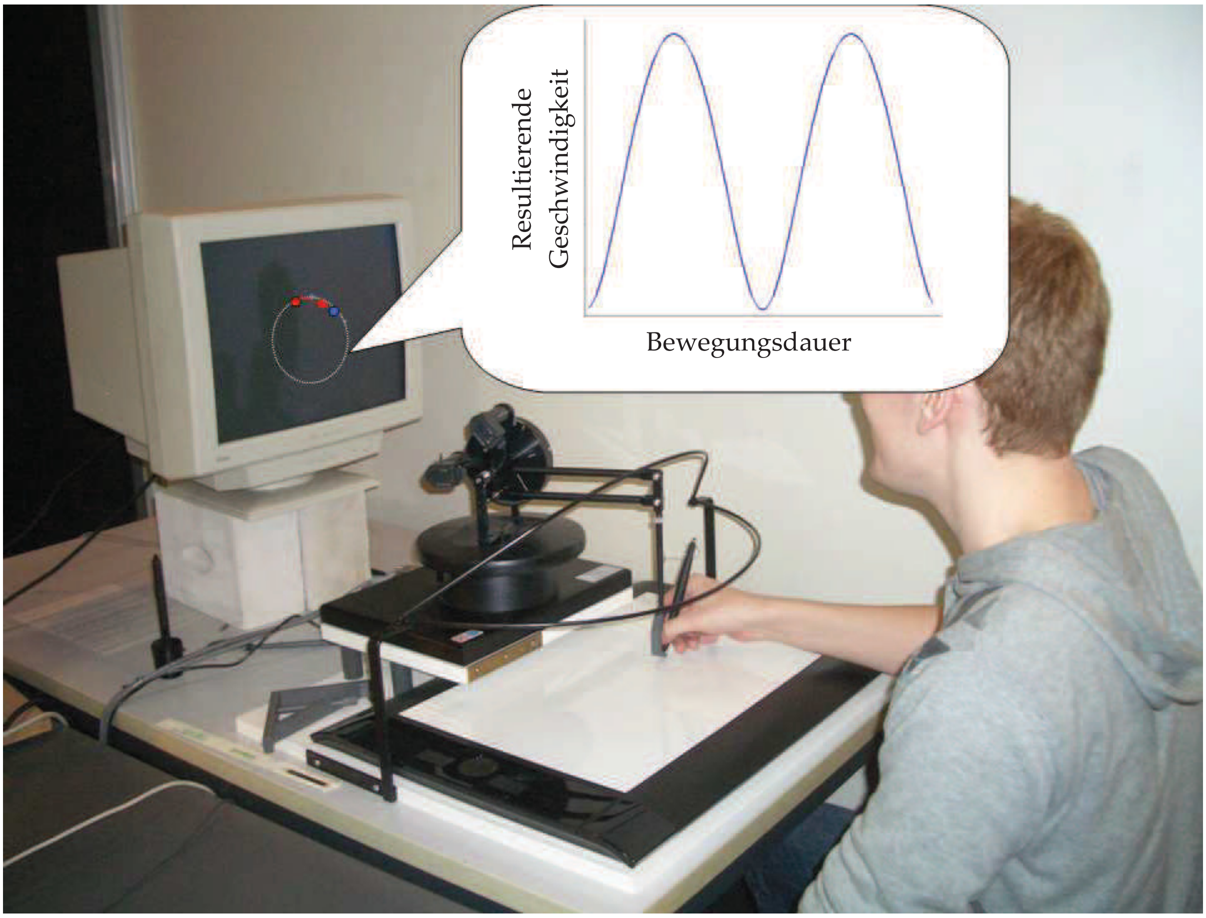

Abbildung 1: Die Probanden in Studie 1 lernten die Bewegung, indem sie eine Trackingaufgabe bearbeiteten. Dabei verfolgten sie mit ihrem Cursor (rot) einen Punkt (blau), welcher sich mit elliptischem Geschwindigkeitsprofil auf einer Kreisbahn auf dem Bildschirm bewegte. In der anschließenden Testphase versuchten die Probanden die Bewegung frei zu reproduzieren.

2.2 Studie 2: Der Einfluss eines haptischen Robotertrainings auf verschiedene Arten motorischen Timings

Die Effekte eines haptischen Robotertrainings auf verschiedene Arten motorischen Timings wurden in Studie 2 differenziert untersucht. Dazu bearbeitete eine Versuchsgruppe eine emergente und eine andere eine diskrete Timingaufgabe in einem Synchronisierungs-Fortführungs-Paradigma. Die Probanden zeichneten in der Synchronisierungsphase Kreise (emergent: kontinuierlich oder diskret: intermittierend) und stimmten ihre Bewegungen dabei mit dem Takt eines Metronoms ab (siehe Abbildung 2). Dabei wurden die Probanden der Experimentalgruppe haptisch von einem Roboter geführt, während die Kontrollprobanden ihre Zeichenbewegungen frei synchronisieren mussten. In der anschließenden Fortführungsphase wurden das Metronom sowie die Roboterunterstützung der Experimentalgruppe abgestellt, und die Probanden sollten ihre Bewegungen mit dem entsprechenden Timing möglichst genau fortführen.

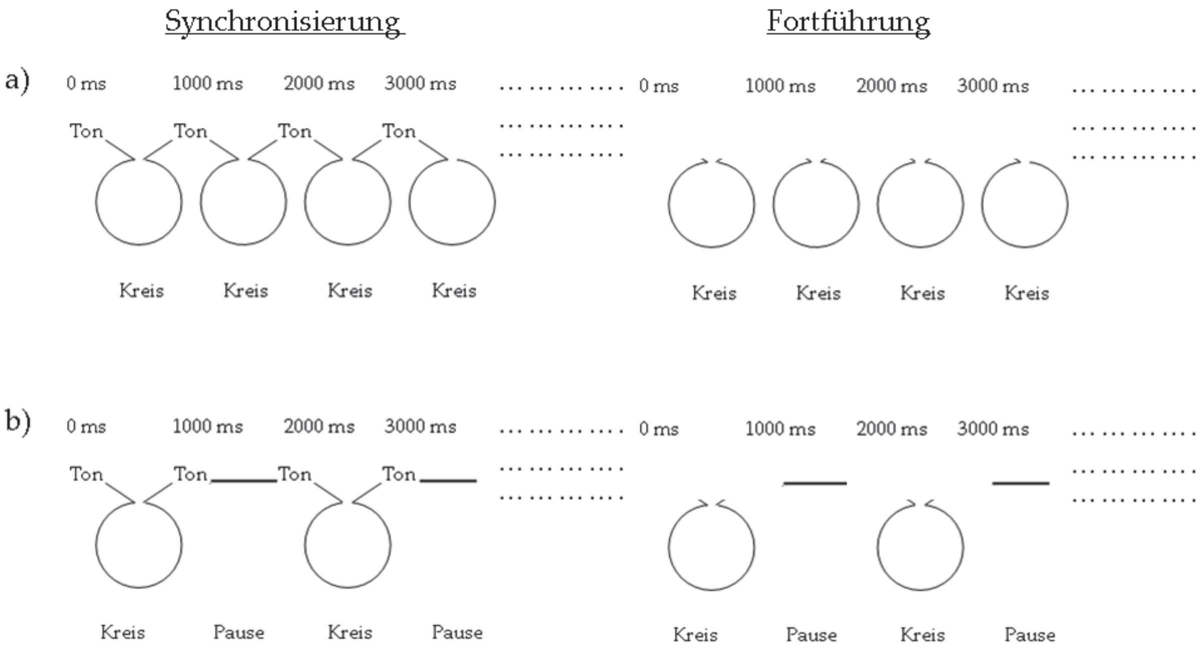

Abbildung 2: In Studie 2 produzierte ein Metronom alle 1000 ms einen Ton. Die Probanden mit der emergenten Timingaufgabe zeichneten kontinuierlich Kreise zwischen jeweils zwei Tönen (a). Probanden mit der diskreten Timingaufgabe pausierten für ein Tonintervall nach jedem Kreis (b). In der anschließenden Fortführungsphase wurde das Metronom abgeschaltet und die Probanden versuchten das jeweilige Timing aus der Synchronisierungsphase beizubehalten.

Die Leistung der Probanden, sowohl während der Synchronisierungs- als auch während der Fortführungsphasen, wurde hinsichtlich der Genauigkeit von absolutem und relativem Timing analysiert, wobei letzteres nur für die diskrete Timingaufgabe relevant war. Während roboterunterstützte Probanden in beiden Timingaufgaben, emergent und diskret, in der Synchronisierungsphase den Kontrollprobanden gegenüber überlegen waren, verschwanden in der Fortführungsphase die Unterschiede zwischen Experimental- und Kontrollgruppe bei der emergenten Timingaufgabe. Bei der diskreten Timingaufgabe dagegen waren die Probanden, welche zuvor von dem Roboter unterstützt wurden, in ihrem relativen Timing weiterhin genauer als die Kontrollprobanden. Die Ergebnisse lassen vermuten, dass besonders das Erlernen von relativem Timing durch ein haptisches Robotertraining gefördert werden könnte. Es ist wahrscheinlich, dass ein solches Training vor allem für das Erlernen solcher Bewegungsmerkmale von Vorteil ist, welche visuell oder verbal nur schwer vermittelbar sind. Relatives Timing scheint ein solches Merkmal zu sein.

2.3 Studie 3: Haptische Roboterunterstützung erleichtert das Erlernen von dynamischen, aber nicht von räumlichen Bewegungsmerkmalen

In Studie 3 wurden die Effekte verschiedener Demonstrationsmodalitäten auf das Erlernen von dynamischen und räumlichen Bewegungsmerkmalen untersucht. Die Bewegung mit dem entsprechenden Geschwindigkeitsprofil wurde zunächst visuell, haptisch oder visuell-haptisch demonstriert. Im Anschluss reproduzierten die Probanden diese Bewegung in zwei alternierenden Testbedingungen, haptisch und visuell-haptisch (siehe Abbildung 3). Die Leistung der drei Versuchsgruppen während der Testphase wurde bezüglich der Genauigkeit räumlicher und dynamischer Bewegungsmerkmale analysiert. Es zeigte sich, dass Probanden, welchen die Bewegung haptisch demonstriert wurde, ihre Bewegungen genauer in Bezug auf dynamische Aspekte ausführten, während Probanden mit visueller Demonstration genauer in Bezug auf räumliche Bewegungsmerkmale waren. Die Kombination von visueller und haptischer Demonstration führte zu keiner nennenswerten Verbesserung, weder bezüglich dynamischer noch in Bezug auf räumliche Aspekte. Zusätzliche visuelle Rückmeldung in der Testphase führte in allen Gruppen zu genaueren Bewegungen. Die Ergebnisse stützen die Hypothese, dass ein haptisches Robotertraining vor allem das Erlernen dynamischer Bewegungsmerkmale fördert.

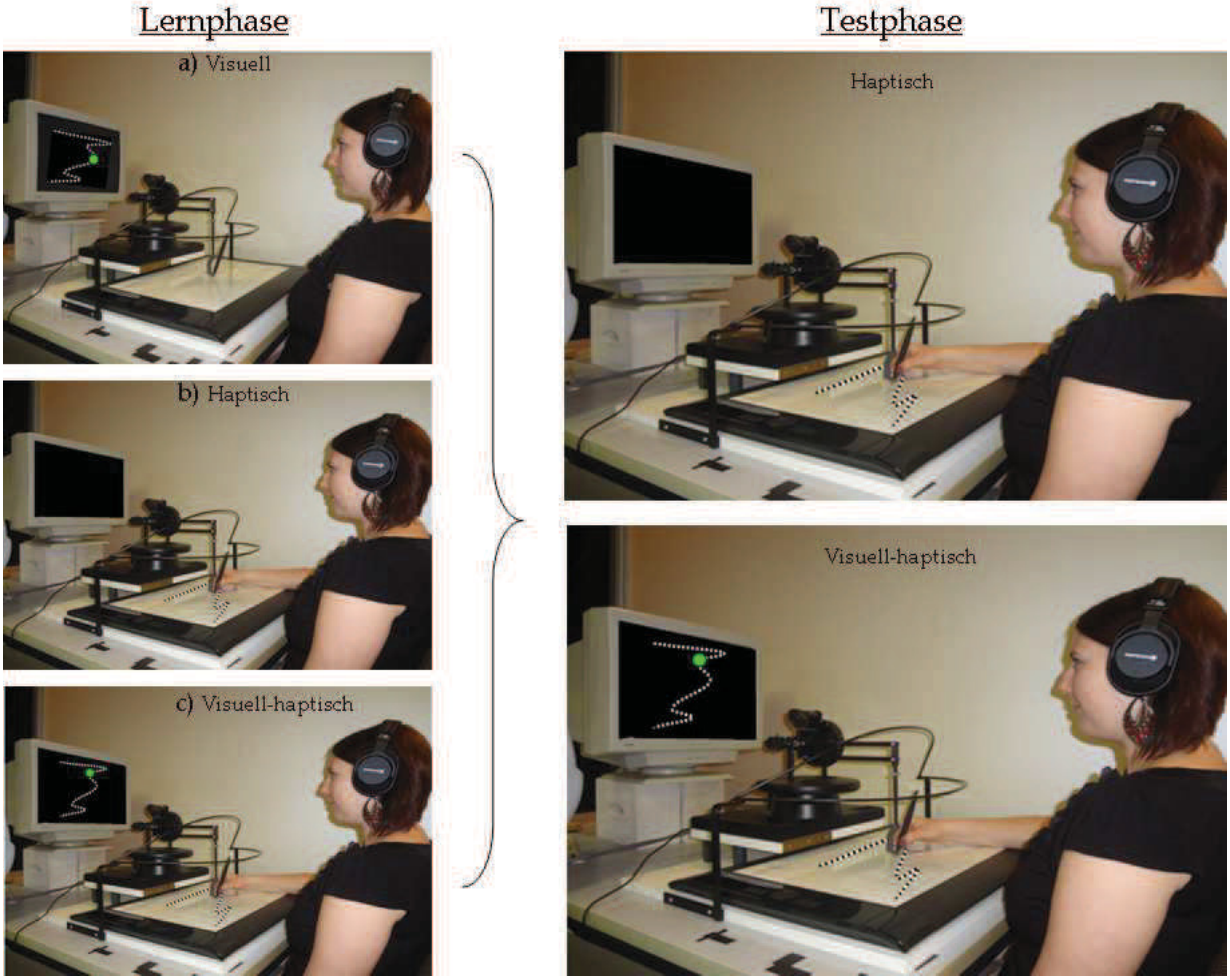

Abbildung 3: In Studie 3 wurde den Probanden die Bewegung in der Lernphase zunächst entweder visuell (a), haptisch (b) oder visuell-haptisch (c) demonstriert. In der anschließenden Testphase reproduzierten die Probanden die Bewegung abwechselnd ohne und mit visueller Rückmeldung.

3 Diskussion und Ausblick

Die drei beschriebenen Studien konnten dazu beitragen, die Effekte eines haptischen Robotertrainings auf das Erlernen von dynamischen und räumlichen Bewegungsmerkmalen genauer zu differenzieren. Zusammenfassend lässt sich festhalten, dass

(1) das Erlernen von dynamischen Bewegungsmerkmalen durch ein haptisches Robotertraining unterstützt werden kann, da diese anders nur schwer vermittelt werden können.

(2) der Grad der Effektivität eines solchen Trainings dabei von den Anforderungen der Aufgabe abhängt: Je schwerer ein dynamisches Merkmal visuell oder verbal kommuniziert werden kann, desto effektiver ist ein haptisches Training für dessen Erlernen.

(3) ein haptisches Robotertraining keine weiteren Vorteile für das Erlernen von räumlichen Bewegungsmerkmalen mit sich bringt, da diese visuell genauer erfasst werden können.

Studie 1 lieferte keine eindeutigen Hinweise auf die Effekte eines haptischen Robotertrainings auf das motorische Lernen. Die Probanden sollten lernen, Bewegungen mit einem unnatürlichen Geschwindigkeitsprofil, welches einem generellen Bewegungsgesetzt widerspricht, auszuführen. Da bisher nur in einer Untersuchung (Beets, Rösler & Fiehler, 2010) gezeigt werden konnte, dass Lernen entgegen dieser Gesetzmäßigkeit überhaupt möglich ist, ist es denkbar, dass die gewählte Aufgabe möglicherweise zu schwierig war, um Unterschiede in der Effektivität verschiedener Trainingsmethoden nachzuweisen. Die recht schlechte Leistung in der Testphase von sowohl Kontroll- als auch Experimentalprobanden unterstützt diese Vermutung. Methodisch lässt sich die relativ kurze Lernphase kritisieren, da davon auszugehen ist, dass das Lernen der Überwindung lebenslang manifestierter Bewegungsgesetze eine längere Lernperiode über mehrere Tage erfordert. Die Hypothese, dass dynamische Bewegungsaspekte von einem haptischen Robotertraining profitieren, konnte nur teilweise bestätigt werden. Zwar waren die Probanden, welche zuvor vom Roboter geführt wurden, genauer bezüglich der Modulation des Geschwindigkeitsprofils der

Bewegung. Dieser Effekt schien allerdings primär durch eine Nebenerscheinung der Roboterführung zu Stande gekommen zu sein. Diese Führung sorgte dafür, dass das zu verfolgende Zielobjekt und der Cursor der Probanden stets übereinander lagen. Die Beschleunigungen im Laufe der Bewegung fielen somit weniger auf als in der Kontrollgruppe, in der sich die Probanden an diesen Stellen beeilen mussten, damit Zielobjekt und Cursor nicht zu weit auseinander drifteten. Die Effekte durch die haptische Demonstration wurden somit höchstwahrscheinlich durch diese visuellen Nebeneffekte überlagert, sodass keine eindeutigen Rückschlüsse auf erstere möglich sind.

Die Ergebnisse der Studien 2 und 3 bestätigen die Hypothese, dass ein haptisches Robotertraining das Erlernen dynamischer Bewegungsaspekte fördern kann. In Studie 2 wurde untersucht, ob verschiedene Arten motorischen Timings unterschiedlich stark von einem solchen Training profitieren. Die Ergebnisse zeigten, dass das Robotertraining zu einem verbesserten relativen Bewegungstiming führt, wogegen für das Erlernen von absolutem Timing keine signifikanten Verbesserungen festgestellt wurden. In Studie 3 schließlich wurde die haptische Demonstrationsbedingung mit einer visuellen Demonstration verglichen. Es konnte gezeigt werden, dass das Robotertraining den Probanden vor allem dabei half, die schnelle Beschleunigung am Anfang der Bewegung zu erlernen. Dies resultierte in einem genaueren Geschwindigkeitsprofil der Experimentalgruppe. Am Ende der Trainingsphase zeigte sich zudem eine Überlegenheit gegenüber der visuellen Demonstrationsgruppe in Bezug auf das absolute Timing der Bewegung. Probanden, welchen die Bewegung visuell demonstriert wurde, waren dagegen genauer in räumlichen Aspekten der Bewegung.

Insgesamt sprechen die Ergebnisse dafür, dass jeweils solche Bewegungsmerkmale von einem haptischen Robotertraining profitieren, welche nur schwer verbal oder visuell kommuniziert werden können. Dynamische Aspekte wie Timing oder Geschwindigkeit sind besonders schwer zu kommunizieren, und ihr Erlernen scheint deshalb von einem haptischen Training zu profitieren. Räumliche Merkmale können dagegen einfacher verbal und vor allem visuell beschrieben werden und profitieren deswegen weniger von haptischen Trainings. Ob das Erlernen von absolutem oder relativem Timing oder gar Geschwindigkeiten am meisten profitiert, scheint dabei keiner allgemein gültigen Gesetzmäßigkeit zu folgen, sondern ist vielmehr von den jeweiligen Aufgabenanforderungen abhängig und kann im Vorhinein nur schwer bestimmt werden. Generell lässt sich aber vermuten, dass der Vorteil eines haptischen Trainings umso größer ist, je schwieriger es ist, die betreffenden Aspekte auf andere Art und Weise zu vermitteln.

Generell muss angemerkt werden, dass die Vorteile einer haptischen Demonstration durch einen Roboter in den Studien 2 und 3 sowie in früheren Untersuchungen (Reinkensmeyer et al., 2007) eher gering waren. Somit kommt die Frage auf, ob diese wirklich die mit der Entwicklung eines hochspezialisierten Roboters einhergehenden Kosten und Mühen rechtfertigen. Für das Erlernen der in den meisten der diskutierten Studien verwendeten Aufgaben lohnt sich die Entwicklung eines speziellen Roboters wahrscheinlich nicht. Jedoch ist zu bemerken, dass lange Zeit unklar war, welche Aufgaben und Aspekte überhaupt von robotischer Führung profitieren und die pragmatisch ausgewählten Aufgaben dieser Studien zunächst zum Ziel hatten, eben jene zu identifizieren.

Da sich die Annahme, dass haptisches Robotertraining für das Erlernen dynamischer Bewegungsaspekte hilfreich ist, nun verdichtet hat, können zukünftige Untersuchungen in stringenterer Weise darauf abzielen, Aufgaben und Anwendungsbereiche zu identifizieren, welche auf der einen Seite dynamische Aspekte als kritische Komponenten enthalten, sodass das Training durch einen Roboter überhaupt erfolgversprechend ist, und deren Unterstützung auf der anderen Seite lohnenswert erscheint. Letzteres könnte der Fall sein, wenn es gelingt, einen robotischen Prototyp zu entwickeln, welcher von einer Vielzahl von Personen genutzt werden kann. Der robotische Rollstuhl von Marchal-Crespo et al. (2010) wäre ein passendes Beispiel im therapeutischen Bereich. Des Weiteren kann sich die Entwicklung spezialisierter Roboter aber auch dann lohnen, wenn selbst kleinste Leistungsverbesserungen bei einer geringen Anzahl spezieller Nutzer wünschenswert sind. Denkbar wären hier medizinische Trainingsroboter, welche Ärzte trainieren und so zu besseren chirurgischen Resultaten führen könnten.

Neben der Identifikation gewichtiger Anwendungsszenarien kann auch die Art der Roboterführung optimiert werden, um den Nutzen haptischer Trainings zu erhöhen. Wie in der Einleitung bereits diskutiert, tritt bei einer kontinuierlichen Unterstützung häufig ein Phänomen namens „Slacking“ auf – eine Abnahme in der Motivation, Aufmerksamkeit und Anstrengung der Probanden (Marchal-Crespo & Reinkensmeyer, 2009). Um diesem Problem entgegen zu wirken schlagen einige Autoren vor, die Stärke der Unterstützung zu variieren. Dies kann zum Einen geschehen, indem Durchgänge ohne Unterstützung in das Robotertraining eingestreut werden (Winstein, et al., 1994). Somit werden Fehler zugelassen, Versuch-und-Irrtum-Lernen wird ermöglicht und die Variabilität des Trainings wird erhöht. Alternativ können adaptive Strategien verwendet werden, bei welchen die Stärke der Unterstützung an das Fertigkeitsniveau des Schülers angepasst und mit der Zeit langsam ausgeblendet wird – entweder auf Basis fixer, zuvor berechneter Lernkurven (z. B. Bayart, Pocheville & Kheddar, 2005) oder indem die Leistung des Schülers ständig online aufgezeichnet und die Stärke der Unterstützung dementsprechend angepasst wird (Huegel & O'Malley, 2010; Li, Huegel, Patoglu, & O'Malley, 2009; Reinkensmeyer, Aoyagi, Emken, Galvez, Ichinose, Kerdanyan, Maneekobkunwong, Minakata, Nessler, Weber, Roy, de Leon, Bobrow, Harkema & Edgerton, 2004; Yokokohji et al., 1996).

Literatur

Adams, J. A. (1971). A closed-loop theory of motor learning. *Journal of Motor Behavior, 3,* 111-150.

Aisen, M. L., Krebs, H. I., Hogan, N., McDowell, F. & Volpe, B. T. (1997). The effect of robot-assisted therapy and rehabilitative training on motor recovery following stroke. *Archives of Neurology, 54,* 443-446.

Banala, S. K., Kim, S. H., Agrawal, S. K. & Scholz, J. P. (2009). Robot assisted gait training with active leg exoskeleton (ALEX). *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 17.*

Basteris, A. & Sanguineti, V. (2011). Toward 'optimal' schemes of robot assistance to facilitate motor skill learning. *Engineering in Medicine and Biology Society, EMBC, 2011 Annual International Conference of the IEEE.*

Bayart, B., Pocheville, A. & Kheddar, A. (2005). An adaptive haptic guidance software module for I-Touch: example through an handwriting teaching simulation and a 3D maze. *HAVE 2005, Haptic Audio Visual Environments and their Applications, Ottawa, Canada.*

Beets, I. A. M., Rösler, F. & Fiehler, K. (2010). Nonvisual motor learning improves visual motion perception: Evidence from violating the two-thirds power law. *Journal of Neurophysiology, 104,* 1612-1624.

Blandin, Y., Lhuisset, L. & Proteau, L. (1999). Cognitive Processes Underlying Observational Learning of Motor Skills. *The Quarterly Journal of Experimental Psychology, 52A,* 957-979.

Bluteau, J., Coquillart, S., Payan, Y. & Gentaz, E. (2008). Haptic guidance improves the visuo-manual tracking of trajectories. *PLoS ONE, 3,* e1775.

Carel, C., Loubinoux, I., Boulanouar, K., Manelfe, C., Rascol, O., Celsis, P. & Chollet, F. (2000). Neural substrate for the effects of passive training on sensorimotor cortical representation: A Study with functional magnetic resonance imaging in healthy subjects. *Journal of Cerebral Blood Flow & Metabolism , 20*, 478-484.

Desmurget, M., Pelisson, D., Rossetti, Y. & Prablanc, C. (1998). From eye to hand: planning goal-directed movements. *Neuroscience and Biobehavioral Reviews, 22,* 761-788.

Emken, J. L., Benitez, R. & Reinkensmeyer, D. J. (2007). Human-robot cooperative movement training: Learning a novel sensory motor transformation during walking with robotic assistance-as-needed. *Journal of Neuroengineering and Rehabilitation, 4.*

Feygin, D., Keehner, M. & Tendick, F. (2002). Haptic guidance: Experimental evaluation of a haptic training method for a perceptual motor skill. *Proceedings of 10th International Symposium on Haptic Interfaces for Virtual Environment and teleoperator Systems (Haptics 2002)*, 40-47.

Fitts, P. M. (1964). Perceptual-motor skill learning. In A. W Melton (Hrsg.). *Categories of human learning.* New York: Academic Press.

Georgopoulos A. P. (2002). Cognitive motor control: spatial and temporal aspects. *Current Opinion in Neurobiology, 12*, 678-683.

Ghez, C., Gordon, J. & Ghilardi, M. F. (1995). Impairments of reaching movements in patients without proprioception. II. Effects of visual information on accuracy. *Journal of Neurophysiology, 73,* 361-372.

Ghez, C., Gordon, J., Ghilardi, M. F, Christakos, C. N. & Cooper, S. E. (1990). Roles of proprioceptive input in the programming of arm trajectories. *Cold Spring Harbor Symposia on Quantitative Biology, 55*, 837-847.

Gillespie, R. B., O'Modhrain, M. S., Tang, P., Zaretzky, D. & Pham, C. (1998). The virtual teacher. *ASME International Mechanical Engineering Conference and Exposition, Anaheim, CA.*

Grindlay, G. (2008). Haptic guidance benefits musical motor learning. *Proceedings of Symposium on Haptic interfaces for Virtual Environment and Teleoperator Systems*, 397-404.

Gordon, J., Ghilardi, M. F. & Ghez, C. (1995). Impairments of reaching movements in patients without proprioception. I. Spatial Errors. *Journal of Neurophysiology, 73*, 347-360.

Henmi, K. & Yoshikawa, T. (1998). Virtual lesson and its application to virtual calligraphy system. *Proceedings of the 1998 IEEE International Conference on Robotics & Automation*, *2*, 1275-1280.

Ho, L. & Shea, J. B. (1978). Effects of relative frequency of knowledge of results on retention of a motor skill. *Perceptual and Motor skills*, 46, 859-866.

Huegel, J. C. & O'Malley, M. K. (2010). Progressive haptic and visual guidance for training in a virtual dynamic task. *IEEE Symposium on Haptic Interfaces for Virtual Environments and Teleoperator Systems,* 343-350.

Jordan, M. I. (1996). Computational aspects of motor control and motor learning. In H. Heuer & S. W. Keele (Hrsg.). *Handbook of Perception and Action. Volume two - Motor Skills*. San Diego, CA: Academic Press Inc.

Kahn, L. E., Zygman, M. L., Rymer, W. Z. & Reinkensmeyer, D. J. (2006). Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study. *Journal of NeuroEngineering and Rehabilitation, 3.*

Kawato, M., Furukawa, K. & Suzuki, R. (1987). A hierarchical neural-network model for control and learning of voluntary movement. *Biological Cybernetics, 57,* 169-185.

Krakauer, J. W., Ghilardi, M. F. & Ghez, C. (1999). Independent learning of internal models for kinematic and dynamic control of reaching. *Nature Neuroscience, 2,* 1026-1031.

Laguna, P. L. (2000). The effect of model observation versus physical practice during motor skill acquisition and performance. *Journal of Human Movement Studies, 39*, 171-191.

Lee, J. & Choi, S. (2010). Effects of haptic guidance and disturbance on motor learning: Potential advantage of haptic disturbance. *2010 IEEE Haptics Symposium, 2010.*

Lee, T. D., Magill, R. A. & Weeks, D. J. (1985). Influence of practice schedule on testing schema theory predictions in adults. *Journal of Motor Behavior, 17*, 283-299.

Li, Y., Huegel, J. C., Patoglu, V. & O'Malley, M. K. (2009). Progressive shared control for training in virtual environments. *Proceedings of the Third Joint EuroHaptics Conference and Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems,* 332-337.

Liu, J., Cramer, S. C. & Reinkensmeyer, D. J. (2006). Learning to perform a new movement with robotic assistance: comparison of haptic guidance and visual demonstration. *Journal of NeuroEngineering and Rehabilitation, 3.*

Marchal-Crespo, L., Furumasu J. & Reinkensmeyer D. J. (2010) A robotic wheelchair trainer: design overview and a feasibility study. *Journal of NeuroEngineering and Rehabilitation*, 7.

Marchal-Crespo, L. & Reinkensmeyer, D. J. (2008a). Haptic guidance can improve motor learning of a steering task. *Journal of Motor Behaviour, 40,* 545-556.

Marchal-Crespo, L. & Reinkensmeyer, D. J. (2008b) Effect of robotic guidance on motor learning of a timing task. *Proceedings of the 2nd Biennial IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, 199-204.

Marchal-Crespo, L. & Reinkensmeyer, D. J. (2009). Review of control strategies for robotic movement training after neurologic injury. *Journal of NeuroEngineering and Rehabilitation, 6.*

Milot, M.-H., Marchal-Crespo, L., Green, C. S., Cramer, S. C. & Reinkensmeyer, D. J. (2010). Comparison of error-amplification and haptic-guidance training techniques for learning of a timing-based motor task by healthy individuals. *Experimental Brain Research, 201,* 119-131.

Palluel-Germain, R., Bara, F., Hillairet de Boisferon, A., Hennion, B., Gouagout, P. & Gentaz, E. (2006). Early handwriting acquisition: Evaluation of Telemaque, a new visuo-haptic interface. *Proceedings of EuroHaptics*, 551-554.

Palluel-Germain, R., Bara, F., Hillairet de Boisferon, A., Hennion, B., Gouagout, P. & Gentaz, E. (2007). A visuo-haptic device – Telemaque – increases kindergarten children's handwriting acquisition. *Proceedings of IEEE World Haptics 2007*, 72-77.

Prange, G. P., Jannink, M. J., Groothuis-Oudshoorn, C. G., Hermens, H. J. & Ijzerman, M. J. (2006). Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *Journal of Rehabilitation Research and Development, 43,* 171-184.

Reinkensmeyer, D. J., Aoyagi, D., Emken, J. L., Galvez, J. A., Ichinose, W., Kerdanyan, G., Maneekobkunwong, S., Minakata, K., Nessler, J. A., Weber, R., Roy, R. R. , de Leon, R., Bobrow, J. E., Harkema, S. J. & Edgerton, V. R. (2004). Tools for understanding and optimizing robotic gait training. *Journal of Rehabilitation Research and Development, 43,* 657-670.

Reinkensmeyer, D. J., Emken, J. K. & Cramer, S. C. (2004). Robotics, motor learning, and neurological recovery. *Annual Review of Biomedical Engineering, 6*, 497-525.

Reinkensmeyer, D. J., Galvez, J. A., Marchal-Crespo, L., Wolbrecht, E. T. & Bobrow, J. E. (2007). Some key problems for robot-assisted movement therapy research: a perspective from the University of California at Irvine. *Proceedings of the 2007 IEEE International Conference on Rehabilitation Robotics,* 1009-1025.

Reinkensmeyer, D. J. & Housman, S. J. (2007). "If I cant't do it once, why do it a hundred times?": Connecting volition to movement success in a virtual environment motivates people to exercise the arm after stroke. *Virtual Rehabilitation,* 44-48.

Reinkensmeyer, D. J. & Patton, J. L. (2009). Can robots help the learning of skilled actions? *Exercise and Sport Sciences Reviews, 37,* 43-51.

Sainburg, R. L., Ghilardi, M. F., Poizner, H. & Ghez, C. (1995). Control of limb dynamics in normal subjects and patients without proprioception. *Journal of Neurophysiology, 73*, 820-835.

Sanger, T. D. (2004). Failure of motor learning for large initial errors. *Neural Computation, 16*, 1873-1886.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. *Psychological Review, 82,* 225-260.

Schmidt, R. A. (1985). The search for invariance in skilled movement behavior. *Research Quarterly for Exercise and Sport, 56*, 188-200.

Schmidt, H. (2004). HapticWalker – A novel haptic device for walking simulation. *Proceedings of EuroHaptics*, Munich, Germany.

Schmidt, R. A. & Bjork, R. A. (1992). New conceptualizations of practice: Common principles in three paradigms suggest new concepts for training. *Psychological Science,* 3, 207- 217.

Schmidt, R. A. & Lee, T. D. (1999). *Motor control and learning – a behavioral emphasis*. 3rd Edition. Champaign, IL: Human Kinetics.

Schmidt, R. F. (1998). *Neuro- und Sinnesphysiologie*. 3. Auflage. Berlin: Springer-Verlag.

Shapiro, D. C. & Schmidt, R. A. (1982). The schema theory: Recent evidence and developmental implications. In J. A. S. Kelso and J. E. Clark (Hrsg.). *The development of movement and co-ordination*. New York: Willey.

Shea, C. H. & Kohl, R. M. (1991). Composition of practice: Influence on the retention of motor skills. *Research Quarterly for Exercise and Sport, 62,* 187-195.

Solis, J., Avizzano, C. A. & Bergamasco, M. (2002). Teaching to write japanese characters using a haptic interface. *Proceedings of 10th International Symposium on Haptic* Interfaces for Virtual Environment and teleoperator Sy*stems (Haptics 2002),* 255-262.

Srimathveeravalli, G. & Thenkurussi, K. (2005). Motor skill training assistance using haptic attributes. *Proceedings of the First EuroHaptics Conference and Symposium on Haptic*, 452-457.

Takahashi, C. D., Der-Yeghiaian, L., Le, V., Motiwala, R. R. & Cramer, S. C. (2007). Robot-based hand motor therapy after stroke. *Brain, 131*, 425-437.

Teo, C. L., Burdet, E. & Lim, H. P. (2002). A robotic teacher of chinese handwriting. *Proceedi*ngs of 10*th International Symposium on Haptic Interfaces for Virtual Environment and teleoperator Systems (Haptics 2002),* 335-341.

Terzuolo, C. A. & Viviani, P. (1980). Determinants and characteristics of motor patterns used for typing. *Neuroscience, 5*, 1085-1103.

Weiller, C., Jueptner, M., Fellows, S., Rijntjes, M., Leonhardt, G., Kiebel, S., Müller, S., Diener, H. C. & Thilmann, A. F. (1996). Brain representation of active and passive movements. *Neuroimage, 4*, 105-110.

Winstein, C. J., Pohl, P. S., Cardinale, C., Green, A., Scholtz, L. & Waters, C. S. (1996). Learning a partial-weight-bearing skill: Effectiveness of two forms of feedback. *Physical Therapy, 76*, 985-993.

Winstein, C. J., Pohl, P. S. & Lewthwaite, R. (1994). Effects of physical guidance and knowledge of results on motor learning: Support for the guidance hypothesis. *Research Quarterly for Exercise and Sport, 65*, 316-323.

Yokokohji, Y., Hollis, R. L., Kanade, T., Henmi, K. & Yoshikawa, T. (1996). Toward machine mediated training of motor skill. *IEEE International Workshop on Robot and Human Communication*, 32-37.

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Studie 3:

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The influence of haptic guidance on the production of spatio-temporal patterns

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A B S T R A C T

Haptic guidance by a robot is a recent technology to support motor learning. Its mechanisms and effects are not yet well understood. One of the hypotheses is that learning of temporal characteristics is particularly susceptible to the beneficial effects of robotic guidance. In this study we investigate the influence of robotic guidance on the production of spatio-temporal patterns. Participants practiced to draw circles with the velocity profile of ellipses. Performance during the practice phase, when participants were assisted by a robotic device, as well as during the test phase, when assistance was switched off, was compared to a control group. During practice participants with robotic assistance performed better on all three dependent measures, shape, timing of the velocity modulation, and modulation amplitude. However, these differences between groups largely disappeared in the test phase. Only the difference in the amplitude of the velocity modulation remained, which was more accurate in the robot-guidance group than in the control group. This remaining difference likely results from a secondary effect of robotic guidance, namely the experience of smaller visual errors and weaker velocity modulations during practice.

1. Introduction

During the last decade there is an increasing interest in the benefits and pitfalls of robot-assisted motor learning (for a review see Marchal-Crespo & Reinkensmeyer, 2009). Investigators from various fields study how the nervous system learns to control different types of movement and how robotic

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devices can support this learning. Most research focuses on robot-assisted motor learning of neurological patients (e.g., Kahn, Zygman, Rymer, & Reinkensmeyer, 2006; Marchal-Crespo & Reinkensmeyer, 2009; Prange, Jannink, Groothuis-Oudshoorn, Hermens, & Ijzerman, 2006; Reinkensmeyer, Emken, & Cramer, 2004; Takahashi, Der-Yeghiaian, Le, Motiwala, & Cramer, 2007), but some attention has also been given to the support of motor learning in healthy people (e.g., Emken & Reinkensmeyer, 2005; Liu, Cramer, & Reinkensmeyer, 2006; Reinkensmeyer & Patton, 2009). Here we inquire into the benefits of robot assistance for the learning of an uncommon timing of drawing movements.

Two distinct effects of robot assistance have to be distinguished in principle. The first one is its impact on performance during practice. It is rather unsurprising that robotic support during practice reduces errors (Marchal-Crespo & Reinkensmeyer, 2008; Reinkensmeyer & Patton, 2009), provides somatosensory stimulation (Marchal-Crespo & Reinkensmeyer, 2009), and leads to improved performance. These effects are beneficial in rehabilitation and in dangerous environments, where large errors are undesirable or associated with risks of accidents. In addition they can support the motivation to perform the task practiced.

The second effect of robot assistance is on learning, that is, on performance after practice when the assistance has been removed. According to Reinkensmeyer and Patton (2009), the enhanced performance during practice can be encouraging. In addition there may be non-motivational effects on motor learning. On the other hand, robotic guidance could impede learning, consistent with the majority of findings on the effects of other variants of physical guidance (Schmidt & Lee, 1999). Overall, it is still uncertain whether robot assistance provides any advantage over other training regimes at all and, if it does, which motor-skill characteristics benefit from such assistance.

The motor skills studied are mostly rather gross movement patterns which involve the arm or the leg such as walking (e.g., Emken & Reinkensmeyer, 2005) or reaching (e.g., Kahn et al., 2006; Prange et al., 2006). Fine motor skills, such as those in writing or minimally-invasive surgery, have been considered less frequently. Some studies examined the robotic support of writing or tracking movements of letters (Ben-Pazi, Ishihara, Kukke, & Ranger, 2009; Bluteau, Coquillart, Payan, & Gentaz, 2008; Henmi & Yoshikawa, 1998; Palluel-Germain et al., 2006, 2007; Solis, Avizzano, & Bergamasco, 2002; Teo, Burdet, & Lim, 2002).

Teo et al. (2002) as well as Henmi and Yoshikawa (1998) and Solis et al. (2002) developed a virtual teaching system and performed experiments to investigate its efficiency. They could show that the participants learned to write Chinese characters or calligraphy with the robotic systems. However, none of these research groups compared robot-assisted practice with other teaching methods such as traditional visual demonstrations without haptic guidance. Palluel-Germain et al. (2006,2007) made such a comparison. They developed a visuo-haptic device, Telemaque, which supported handwriting in a training program, and they compared performance before and after the training with that of a control group who practiced in a conventional way. Both in first-grade children (Palluel-Germain et al., 2006) and kindergarten children (Palluel-Germain et al., 2007) fluency in handwriting increased more after training with Telemaque than after control training.

Fluent handwriting is a skill that requires both spatial and temporal precision. There is some evidence that learning of temporal characteristics is particularly susceptible to beneficial effects of robotic guidance (Feygin, Keehner, & Tendick, 2002; Marchal-Crespo & Reinkensmeyer, 2008; Milot, Marchal-Crespo, Green, Cramer, & Reinkensmeyer, 2010), whereas acquisition of spatial characteristics may profit more from visual training (Feygin et al., 2002). However, temporal characteristics can be of different types, and not all of them may benefit from robot assistance. The present experiment was designed to determine the benefits of robot support for the learning of an unusual timing of a simple drawing movement. This is a specific temporal characteristic which is distinct, e.g., from total duration of a movement or its temporal placement relative to an environmental event. More specifically, participants had to draw a circle with the velocity profile typical for drawing an ellipse.

The difficulty of this task is due to the relation between form and velocity in drawing that is known for a long time (e.g., Derwort, 1938). According to Viviani and Terzuolo (1982), a strict relation exists in that curvature and velocity are inversely related so that with increasing curvature velocity decreases and vice versa. The equation which describes this relation is called the 2/3 power law (Viviani & Terzuolo, 1982). According to this law, and according to experimental observations, a circle is drawn with a constant velocity because its curvature is constant, whereas an ellipse is drawn with a

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modulated velocity because curvature varies along its circumference. According to several studies it is very difficult or even impossible to produce movements that violate the 2/3 power law (e.g., Viviani, Campadelli, & Mounoud, 1987; Viviani & Mounoud, 1990), but Beets, Rösler, and Fiehler (2010) recently showed that, in principle, one can learn circular arm movements with an elliptic velocity profile.

Beets, Rösler, and Fiehler (2010) supported their participants by means of a motor-driven crank which enforced a circular path with velocity modulations appropriate for an elliptic path. As noted above, showing that a certain motor skill can be learned with robot support during practice does not imply that robot support has any advantages above other procedures. Therefore we compared the effects of robot-assisted practice with the effects of a non-assisted, but otherwise identical practice regime. The participants practiced to draw circles with the velocity profile of a horizontal ellipse, that is, the resultant velocity was higher at the top and bottom of the circle than at both sides. Since the timing and shape of drawing movements are tightly interrelated, we also assessed the spatial characteristics. During practice participants tracked a moving target either without or with the support of a robot. The moving target provided sort of visual guidance, the robot additional haptic guidance. During tests the velocity-modulated circles had to be drawn without the visible target and without robot assistance.

2. Methods

2.1. Participants

A total of 26 females and 12 males participated in the study. Their age ranged from 18 to 31 years (*M* = 24.2 years, *SD* = 3.10 years). 19 of them practiced with robot support in the experimental group (16 female, 3 male; mean age: 23.5 years), 19 without robot support in the control group (10 female, 9 male; mean age: 24.9 years). All participants were right-handed, had normal or corrected to normal vision and no significant language, motor or neurological dysfunction according to their own declaration. Each participant signed written informed consent and was paid 15 Euro for participation.

2.2. Apparatus

Participants drew with a pen on a digitizer (Wacom Intuos4) which sampled data at 60 Hz. The tip of the pen was attached to the end of a robot arm (Phantom Premium 1.5, SensAble Technologies), as shown in Fig. 1a. The connecting link at the end of the robot arm carried a hole into which the tip of the pen was inserted. The pen was held there by a minute rubber ring inside the walls of the hole, so that it could be tilted freely in all directions on the tablet. Only with respect to horizontal movements the link between robot arm and tip of the pen was rigid. To avoid injuries in case the Phantom got out of control, a safety barrier was placed between Phantom and participant. Fig. 1b shows the whole experimental setup with Phantom, the digitizer and the monitor (Iiyama S902JT VisionMaster Pro 451) which was placed at about 90 cm distance from the participant's eyes.

2.3. Design and procedure

Participants were seated in front of the digitizer in a quiet room, with walls covered by black curtains. They were instructed to watch the screen of the monitor. The room light was switched off during the experiment to prevent participants from watching their hand and the pen. The whole experiment took about one and a half hour. First the instructions were read and two practice trials were performed to allow the participants to familiarize themselves with the apparatus and the task.

Familiarization was followed by five blocks of trials. Each block consisted of a practice phase of 25 trials followed by a test phase of 15 trials. In each trial five circles had to be drawn. In the practice phase participants performed a tracking task. The position of the tip of the pen was mapped on the position of a cursor, a red filled circle of 5 mm diameter. With this cursor participants had to follow the target, a blue filled circle of 5 mm diameter. The target moved on a circular path of 10 cm

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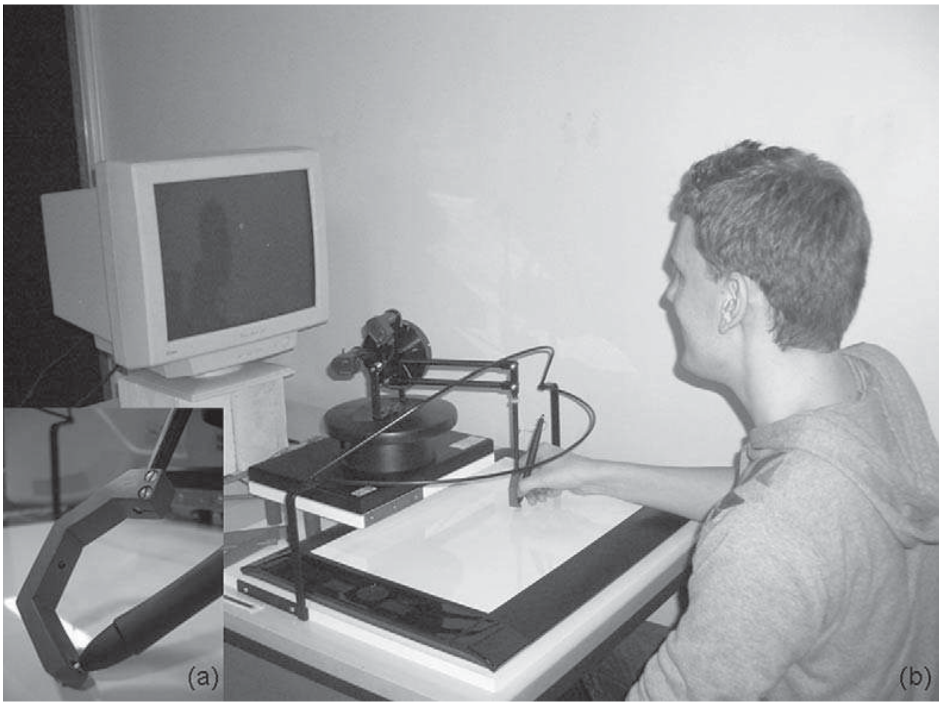

Fig. 1. Apparatus: (a) The tip of the pen was attached to the lower end of the stylus of a Phantom Premium 1.5. (b) Participants were seated in front of a digitizer tablet and faced a monitor.

diameter. Its total movement time for this circle was 3.3 s. The resultant velocity of the target was that appropriate for a horizontal ellipse with a proportion of its vertical to its horizontal axis of 0.5. Thus, velocity was higher at the top and bottom of the circular path (maximum velocity: 122 mm/s) and lower at its left and right side (minimum velocity: 61 mm/s). Neither the target nor the cursor left a visible trace on the screen. The motion of the target was sufficiently slow not to give rise to the perception of an elliptical path, as reported, e.g., by Viviani and Stucchi (1989) who used a movement time of 0.6 rather than 3.3 s.

Participants began each trial at a start position at the extreme right side of the circular path. After the cursor had been aligned with the target for two seconds, the target started to move, and the participants tracked it with the cursor for a total of five circles. During the practice trials the experimental group was assisted by the Phantom. More specifically, at each point in time there was a force field which drove the tip of the pen to its target position at which the cursor was aligned with the target on the monitor. The force was $0.3d$ N, with d as the distance of the current position of the tip of the pen from its target position (upper limit: 10 Newton). Pilot studies had revealed that this force was appropriate to minimize the tracking error in the experimental group. The participants of the control condition also drew with the pen attached to the Phantom device, but there was no haptic guidance as in the experimental group.

In the trials of each test phase participants were required to reproduce the circular trajectory with the elliptic velocity profile. At the beginning of each test trial the target was presented at the rightmost position of the circular path. After participants had aligned the cursor with the target for two seconds, the target disappeared and participants could start their movements. The cursor remained visible but left no trace on the screen. Participants were told to draw five circles and to reproduce the shape and the velocity profile as accurately as possible. After five circles had been drawn, a beep occurred, the target appeared again, and the next trial began.

2.4. Data analysis

The position-time curves of the tip of the pen were low-pass filtered (fourth-order Butterworth, 5 Hz, dual-pass). From the velocities along both dimensions of the plane, which were calculated by a central-difference algorithm, the resultant velocity was computed.

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The trajectory of each trial was segmented into individual cycles by a spatial criterion. A new cycle began whenever the horizontal axis through the start position was passed. For each of the three central cycles of each trial the circularity of the trajectories and the modulation of the resultant velocity were evaluated by means of three dependent variables, a circularity index, a measure of modulation timing of velocity and a measure of modulation amplitude.

The circularity index served to assess deviations from a circular path toward an ellipse. It was determined in the following way. First, a surrounding square was fitted to the recorded path of each cycle. The center of the square served as the midpoint of the roughly circular trajectory. Second, a coordinate system was positioned in this configuration such that its origin was in the midpoint, and its abscissa was aligned with the longest diameter of the trajectory. Third, the radius was determined for each sample point, that is, its distance from the origin of the coordinate system. Fourth, the approximate circle circumscribed by the trajectory was split into four sectors with the diagonals as boundaries. The radii were averaged across the data points of each sector. For a circular path these four means are identical, but for an ellipse the means of the horizontal sectors are larger than the means of the vertical sectors. Fifth, the circularity index was defined as the ratio of the means of the horizontal sectors and the vertical sectors. It is 1 for perfect circularity, and larger values indicate elliptical deviations from circularity (Fig. 2).

The measure of modulation timing of velocity was a cross-correlation. The resultant velocity for each cycle was normalized to a length of 128 data points (with linear interpolation). In addition it was shifted such that mean velocity corresponded to zero. This normalization does not affect the dependent measures, but makes visual inspection and comparison of plotted velocity profiles easier. The target velocity was treated in the same way. Modulation timing was defined as the maximum of the cross-correlation function (Fig. 3). This measure is 1 for perfect temporal regularity of velocity modulation, and smaller than 1 otherwise, that is, when the relative temporal positions of the minima and maxima are not as required. Note that the measure is insensitive to temporal shifts of the whole profile within each cycle, so that maximal resultant velocities that are not exactly at the top and bottom of the circle. In addition the measure is insensitive to variations of scale factors. Therefore it was complemented by the measure of modulation amplitude.

The measure of modulation amplitude of velocity was derived from the peak-to-peak amplitude of the resultant velocity of each cycle, more precisely, from the difference between the means of the two peaks and the two troughs of the profile (Fig. 3). The ideal peak-to-peak amplitude, which was 61 mm/s, was subtracted from the observed one. Thus the measure of modulation amplitude is an error measure which is zero when the amplitude is exactly as required. It is positive for a too strong modulation and negative for a too weak one.

The circularity index and the measures of modulation timing and amplitude were averaged across the middle three cycles of each trial, and these means were averaged across the trials of each block. These individual means were entered in the statistical analyses. Separately for the practice phases

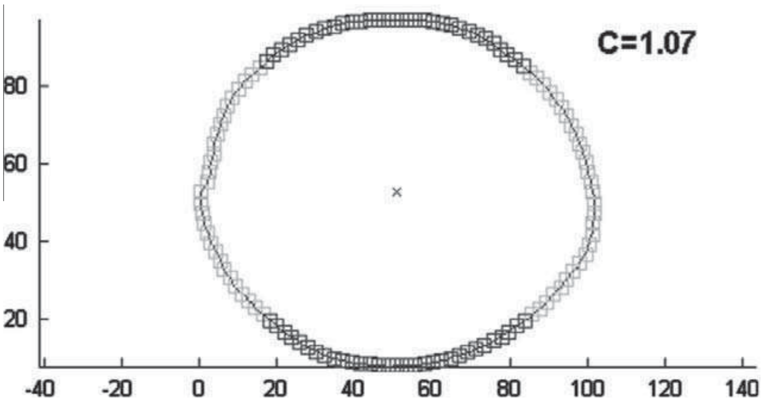

Fig. 2. Shape sample. The average radius of the horizontal segments (light gray) was divided by the average radius of the vertical segments (black), so that 1 represents perfect circularity. The circularity C = 1.07 in this example characterizes a rather elliptic form.

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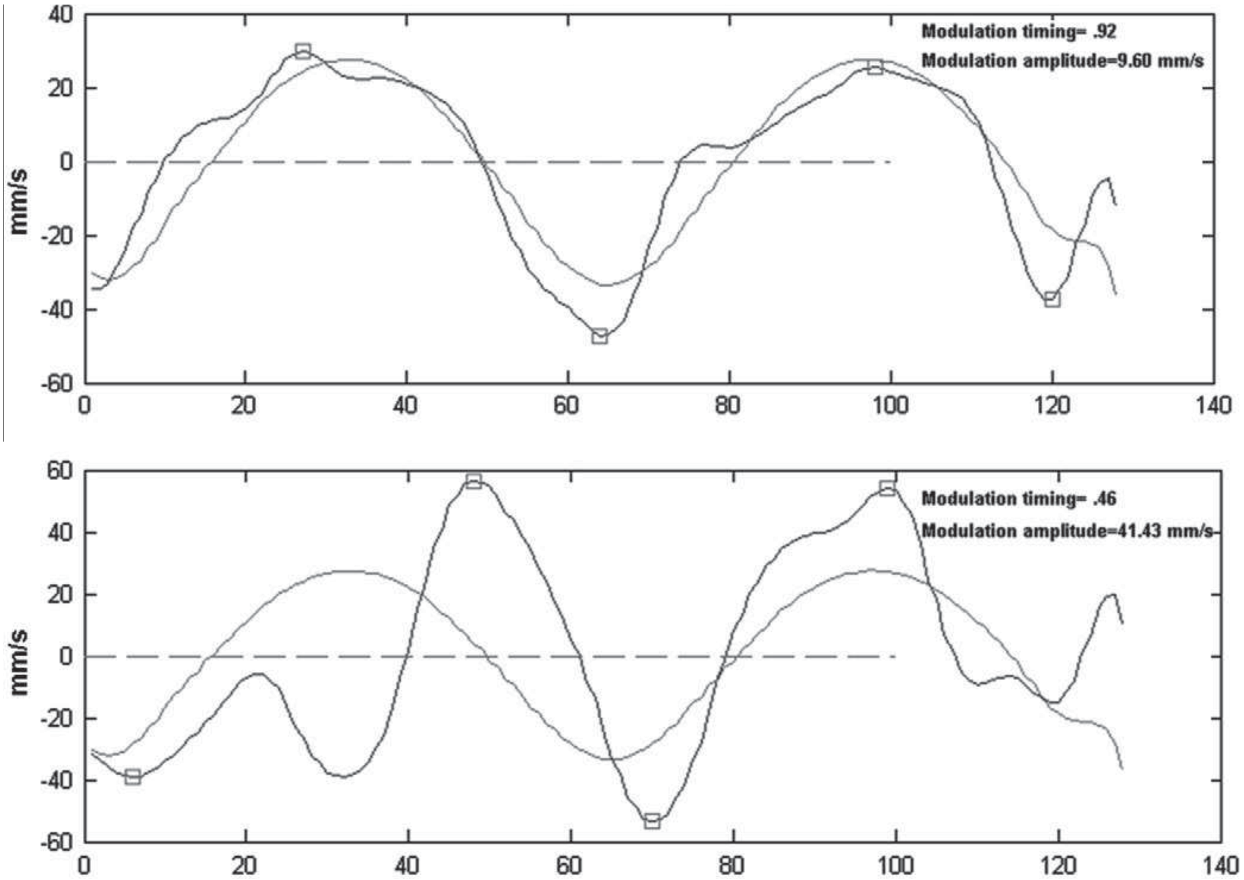

Fig. 3. Two samples of velocity curves. The curves marked by the four squares at the peaks and troughs are the observed velocity profiles, the other curves are the ideal velocity profiles. The precision of modulation timing of resultant velocity is measured by the maximum value of the cross-correlation function. The precision of modulation was measured by the deviation of the peak-to-peak amplitude from the correct amplitude; this error measure is called modulation amplitude for short. The participant of the upper graph succeeded in producing the desired velocity profile and reached a very high cross-correlation value. The modulation amplitude only deviated marginally from the desired amplitude. In contrast, the participant of the lower figure only reached a moderate cross-correlation value and exaggerated the modulation amplitude.

and test phases of the five blocks of trials and the three dependent variables two-way ANOVAs were run with the between-participant factor practice group and the within-participant factor block. Greenhouse-Geisser corrections were applied when appropriate, but the uncorrected degrees of freedom are reported together with the Greenhouse-Geisser epsilon. Effect sizes are given as partial eta-squared.

3. Results

The results of the experiment will be reported first for the practice trials and thereafter for the test trials. Whereas the practice trials reflect the immediate performance effects of the robot assistance, the test trials reflect the effects on learning.

3.1. Practice phase

As expected, the experimental group with robot assistance performed better with respect to both the circularity of the trajectory and the modulation timing and amplitude of resultant velocity (Fig. 4). In the experimental group the mean circularity index was $M = 1.017$ ($SE = .002$), whereas in the control group it was $M = 1.042$ ($SE = .002$), indicating a somewhat elliptical path. The ANOVA revealed the difference between groups to be highly significant, $F(1, 36) = 57.80$, $p < .01$, $\eta_p^2 = .62$. The variation across

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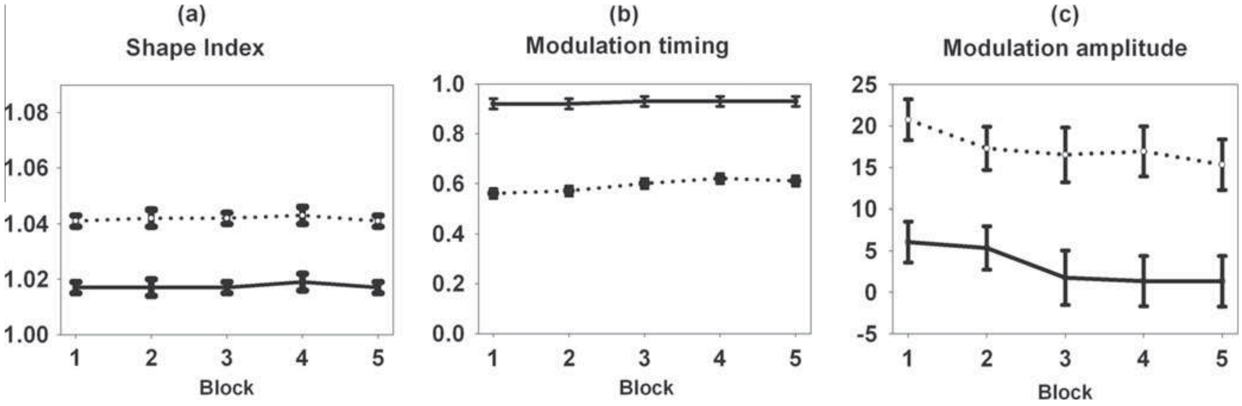

Fig. 4. Shape index (a), modulation timing (b) and modulation amplitude (c) for the experimental (continuous line) and the control group (dotted line) across the 5 blocks during the practice phase. Vertical bars represent standard errors.

blocks, $F(4, 144) = 0.65$, $p = .56$, $\varepsilon = .64$, $\eta_p^2 = .02$, as well as the interaction, $F(4, 144) = 0.09$, $p = .95$, $\varepsilon = .64$, $\eta_p^2 = .00$, were not significant.

In the experimental group the timing of the modulation of resultant velocity was highly regular. The mean modulation timing as measured by the cross-correlation was $M = .93$ ($SE = .02$) and did not vary across blocks. In the control group the mean modulation timing was only $M = .56$ ($SE = .02$) in the first block of trials and reached $M = .62$ ($SE = .02$) in the fourth block (in the fifth block it was $M = .61$, $SE = .02$). The difference between groups was significant, $F(1, 36) = 151.19$, $p < .01$, $\eta_p^2 = .81$. The main effect of block, $F(4, 144) = 5.56$, $p < .01$, $\varepsilon = .66$, $\eta_p^2 = .13$, and the interaction, $F(4, 144) = 3.14$, $p = .03$, $\varepsilon = .66$, $\eta_p^2 = .08$, also reached statistical significance.

In the experimental group the mean modulation amplitude of resultant velocity was $M = 3.16$ mm/s ($SE = 2.53$ mm/s), that is, the amplitude of the modulation was only marginally stronger than required. The exaggeration of the modulation was more pronounced in the control group, for which the mean modulation amplitude was $M = 17.36$ mm/s ($SE = 2.53$ mm/s). The difference between groups was significant, $F(1, 36) = 15.74$, $p < .01$, $\eta_p^2 = .30$, and also the main effect of block reached statistical significance, $F(4, 144) = 3.35$, $p = .05$, $\varepsilon = .41$, $\eta_p^2 = .08$, whereas there was no significant interaction, $F(4, 144) = 0.36$, $p = .65$, $\varepsilon = .41$, $\eta_p^2 = .01$.

3.2. Test phase

The means of the three dependent variables in the test phase are shown in Fig. 5. Both groups produced somewhat elliptic trajectories. The mean circularity indices were $M = 1.065$ ($SE = .004$) for the experimental group and $M = 1.072$ ($SE = .004$) for the control group. The main effect of group was

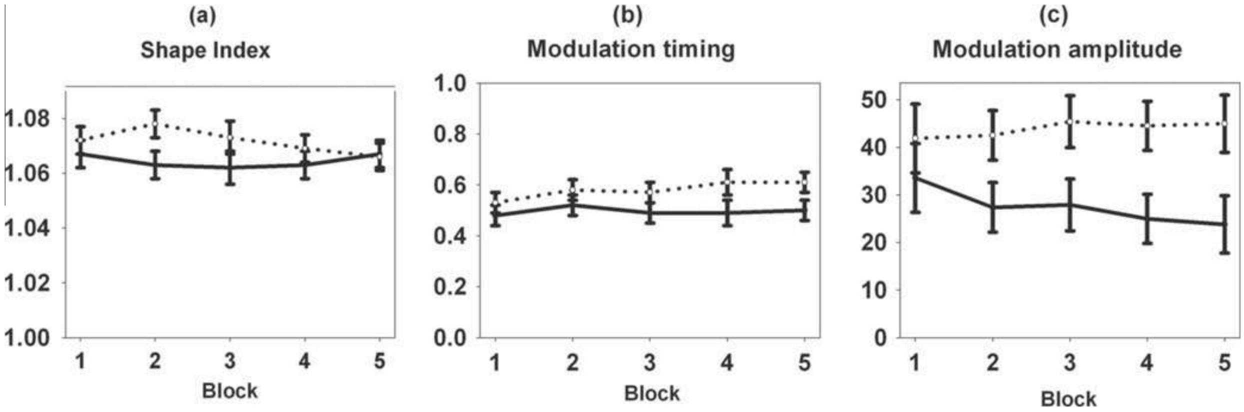

Fig. 5. Shape index (a), modulation timing (b) and modulation amplitude (c) for the experimental (continuous line) and the control group (dotted line) across the 5 blocks during the test phase. Vertical bars represent standard errors.

not significant, $F(1, 36) = 1.38$, $p = .25$, $\eta_p^2 = .04$. Also the main effect of block, $F(4, 144) = 0.61$; $p = .59$, $\varepsilon = .68$, $\eta_p^2 = .02$, and the interaction, $F(4, 144) = 1.48$, $p = .23$, $\varepsilon = .68$, $\eta_p^2 = .04$, failed to reach statistical significance.

The modulation timing of the resultant velocity was similar in both groups, but somewhat higher in the control group. In the experimental group the mean modulation timing was $M = .50$ ($SE = .04$) and in the control group it was $M = .58$ ($SE = .03$). According to the ANOVA the main effect of group fell short of statistical significance, $F(1, 36) = 2.37$, $p = .13$, $\eta_p^2 = .06$, and so did the main effect of block, $F(4, 144) = 2.97$, $p = .06$, $\varepsilon = .52$, $\eta_p^2 = .08$, and the interaction, $F(4, 144) = 1.34$, $p = .27$, $\varepsilon = .52$, $\eta_p^2 = .04$.

Both groups exaggerated the amplitude of the modulation of the resultant velocity, that is, their modulation amplitude was higher than required. As during practice, this exaggeration was more pronounced in the control group ($M = 43.85$ mm/s, $SE = 5.22$ mm/s) than in the experimental group ($M = 27.51$ mm/s, $SE = 5.22$ mm/s). This difference was significant, $F(1, 36) = 4.89$, $p = .03$, $\eta_p^2 = .12$. Whereas the modulation amplitude was consistently high across blocks of test trials in the control group, it declined slightly in the experimental group from a mean of $M = 33.56$ mm/s ($SE = 7.24$ mm/s) in the first block to a mean of $M = 23.76$ mm/s ($SE = 6.03$ mm/s) in the last block. However, neither the main effect of block, $F(4, 144) = 0.45$, $p = .70$, $\varepsilon = .69$, $\eta_p^2 = .01$, nor the interaction, $F(4, 144) = 1.40$, $p = .25$, $\varepsilon = .70$, $\eta_p^2 = .04$, reached statistical significance.

4. Discussion

The present study had been designed to examine the effects of robot assistance on performance and learning of an untypical velocity profile in drawing circles. With respect to the immediate performance effects, our findings are consistent with previous observations that robotic guidance serves to enhance performance and to reduce errors (Marchal-Crespo & Reinkensmeyer, 2008; Reinkensmeyer & Patton, 2009). In the experimental group, who practiced with robot guidance, the trajectories were almost perfectly circular and the velocity profile matched the desired profile quite well with respect to its timing and its modulation amplitude. In contrast, in the control group, who practiced without robot guidance, the trajectories were more elliptic and the modulation timing was less regular. Though there was an improvement across blocks regarding the modulation timing, this group performed the tracking task rather poorly and had difficulties in following the target, perhaps because of its modulated velocity. In addition the modulation amplitude, more precisely, the excess over the correct modulation amplitude, was much stronger than in the experimental group. Both groups showed an improvement in the modulation amplitude across blocks. Thus, all in all the movements experienced by the experimental group during practice were much more accurate than the movements experienced by the control group, but the accurate movements resulted primarily from external forces, generated by the robot, whereas the less accurate movements resulted from self-generated forces.

In the test trials, when robot guidance was switched off in the experimental group, the performance differences between groups largely disappeared. The accurate performance experienced with robot assistance could not be maintained in general. Only one of the differences present during practice was still present in test trials, though it was reduced. This was the difference in the amplitude of the velocity modulation which remained more accurate in the experimental group than in the control group. This difference between groups was not associated with a corresponding difference in the circularity index. Thus it reflects a certain degree of dissociation of curvature and velocity. Because there were no significant differences in modulation timing between groups, our results do not fully support the claim that learning of temporal aspects is qualified to be supported by robotic guidance (Feygin et al., 2002; Marchal-Crespo & Reinkensmeyer, 2008; Milot et al., 2010). Instead the benefits are likely to be limited to certain temporal characteristics.

The finding that robot assistance did not enhance learning of the timing of the velocity modulation, but only of its amplitude, can be taken to suggest that it was caused by a secondary effect of robot guidance. In the experimental group with robot guidance the cursor and the target were almost perfectly aligned throughout the whole practice phase. Therefore velocity modulations were not as obvious in the visual display as in the control group, where the target and the cursor drifted apart when the target was accelerated. Whereas participants in the experimental group modulated the velocity

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fairly accurately in amplitude, participants in the control group learned to rush at points of high velocity and transferred this exaggeration into the test phase. The exaggeration of the velocity modulation in addition could have enhanced the modulation timing in the control group. Participants in the control group could have paid more attention to the more conspicuous velocity changes, resulting in better learning. Several authors (e.g., Connolly & Jones, 1970; Rock & Victor, 1964) have argued that individuals rely more on visual than on kinesthetic feedback. Thus, in the present study the visual indications of the velocity modulation might have been more important for learning than the kinesthetic information, and the visual information was less pronounced in the experimental group than in the control group. Thus the effects of robot guidance per se may have been superposed by the effects of robot guidance on the visual information during practice.

Furthermore, the guidance in the experimental group might have evoked a passive attitude in that the participants did not actively try to track the target. Some authors argued that continuous robotic assistance might lead to decreasing effort, attention, and motivation (Marchal-Crespo & Reinkensmeyer, 2009). As also stated by Schmidt and Lee (1999), guidance prevents the participants from experiencing and correcting errors and could thus be obstructive for the learning of movements. Therefore assistance that is adapted to the skill level of the participant or an assistance strategy that occasionally allows the participant to experience errors might be more beneficial.

In general performance was not very good in both groups. It is feasible that this is a result of the short duration of practice. The movement that was to be learned was a non-biological one, and participants might need several training sessions distributed over more than one day to learn it. The slightly diverging practice curves for the modulation timing and the modulation amplitude indicate that the asymptote had not yet been reached. On the other hand, the observation of practice effects after a single session is consistent with the findings of Beets et al. (2010) . From the slight divergence of the practice curves one could expect that the difference between the two practice groups with respect to modulation amplitude could become more pronounced in the long run. In addition a superiority of the control group with respect to modulation timing could develop, but the present data do not allow a sufficiently firm conclusion in this respect.

As mentioned earlier by Reinkensmeyer, Galvez, Marchal-Crespo, Wolbrecht, and Bobrow (2007), the mechanisms of motor learning and the possible benefits by a robotic training are still not well understood. Additional investigations with other motor timing tasks as well as other assistance control strategies and a longer training period over several days shall further clarify the question if and under which conditions learning of temporal characteristics can be enhanced by robot assistance.

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References

Beets, I. A. M., Rösler, F., & Fiehler, K. (2010) . Non-visual motor learning improves visual motion perception: Evidence from violating the two-thirds power law. *Journal of Neurophysiology, 104*, 1612–1624.

Ben-Pazi, H., Ishihara, A., Kukke, S., & Ranger, T. D. (2009). Increasing viscosity and inertia using a robotically controlled pen improves handwriting in children. *Journal of Child Neurology, 25*, 674–680.

Bluteau, J., Coquillart, S., Payan, Y., & Gentaz, E. (2008). Haptic guidance improves the visuo-manual tracking of trajectories. *PLoS ONE, 3*, e1775.

Connolly, K., & Jones, B. (1970). A developmental study of afferent-reafferent integration. *British Journal of Psychology, 61*, 259–266.

Derwort, A. (1938). Untersuchungen über den Zeitablauf figurierter Bewegungen beim Menschen. *Pflügers Archiv für die gesamte Physiologie, 240*, 661–675.

Emken, J. L., & Reinkensmeyer, D. J. (2005). Robot-enhanced motor learning: Accelerating internal model formation during locomotion by transient dynamic amplification. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 13*, 33–39.

Feygin, D., Keehner, M., & Tendick, F. (2002). Haptic guidance: Experimental evaluation of haptic training method for a perceptual motor skill. *Proceedings of 10th International Symposium on Haptic Interfaces for Virtual Environment and teleoperator Systems (Haptics 2002)*, 40–47.

Henmi, K., & Yoshikawa, T. (1998). Virtual lesson and Ist application to virtual calligraphy system. *Proceedings of the 1998 IEEE International Conference on Robotics & Automation, 2*, 1275–1280.

Kahn, L. E., Zygman, M. L., Rymer, W. Z., & Reinkensmeyer, D. J. (2006). Robot-assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: A randomized controlled pilot study. *Journal of NeuroEngineering and Rehabilitation, 3*, 1–13.

Liu, J., Cramer, S. C., & Reinkensmeyer, D. J. (2006). Learning to perform a new movement with robotic assistance. comparison of haptic guidance and visual demonstration. *Journal of NeuroEngineering and Rehabilitation, 3*, 495–506.

Marchal-Crespo, L., & Reinkensmeyer, D. J. (2008). Haptic guidance can improve motor learning of a steering task. *Journal of Motor Behaviour, 40*, 545–556.

Marchal-Crespo, L., & Reinkensmeyer, D. J. (2009). Review of control strategies for robotic movement training after neurologic injury. *Journal of NeuroEngineering and Rehabilitation, 6*, 20.

Milot, M.-H., Marchal-Crespo, L., Green, C. S., Cramer, S. C., & Reinkensmeyer, D. J. (2010). Comparison of error-amplification and haptic-guidance training techniques for learning of a timing-based motor task by healthy individuals. *Experimental Brain Research, 201*, 119–131.

Palluel-Germain, R., Bara, F., Hillairet de Boisferon, A., Hennion, B., Gouagout, P., & Gentaz, E. (2006). Early handwriting acquisition : Evaluation of Telemaque, a new visuo-haptic interface. *Proceedings of EuroHaptics, 551*, 554.

Palluel-Germain, R., Bara, F., Hillairet de Boisferon, A., Hennion, B., Gouagout, P., & Gentaz, E. (2007). A visuo-haptic device – Telemaque – increases kindergarten children's handwriting acquisition. *Proceedings of IEEE World Haptics, 2007*, 72–77.

Prange, G. P., Jannink, M. J., Groothuis-Oudshoorn, C. G., Hermens, H., & IJzerman, M. J. (2006). Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *Journal of Rehabilitation Research & Development, 43*, 171–184.

Reinkensmeyer, D. J., Emken, J. K., & Cramer, S. C. (2004). Robotics, motor learning, and neurological recovery. *Annual Review of Biomedical Engineering, 6*, 497–525.

Reinkensmeyer, D. J., Galvez, J. A., Marchal-Crespo, L., Wolbrecht, E. T., & Bobrow, J. E. (2007). Some key problems for robot-assisted movement therapy research: a perspective from the university of california at Irvine. *Proceedings of the 2007 IEEE International Conference on Rehabilitation Robotics, 11*, 1009–1025.

Reinkensmeyer, D. J., & Patton, J. L. (2009). Can robots help the learning of skilled actions? *Exercise and Sport Sciences Reviews, 37*, 43–51.

Rock, I., & Victor, J. (1964). Vision and touch: An experimentally created conflict between the two senses. *Science, 143*, 594–596.

Schmidt, R. A., & Lee, T. D. (1999). *Motor control and learning – A behavioural emphasis* (3rd ed.), pp. 316–317.

Solis, J., Avizzano, C. A., & Bergamasco, M. (2002). Teaching to write japanese characters using a haptic interface. *Proceedings of 10th International Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems (Haptics 2002)*, 255–262.

Takahashi, C. D., Der-Yeghiaian, L., Le, V., Motiwala, R. R., & Cramer, S. C. (2007). Robot-based hand motor therapy after stroke. *Brain, 131*, 425–437.

Teo, C., Burdet, E., & Lim, H. (2002). A robotic teacher of Chinese handwriting. *Proceedings of 10th International Symposium on Haptic Interfaces for Virtual Environment and teleoperator Systems (Haptics 2002)*, 335–341.

Viviani, P., Campadelli, P., & Mounoud, P. (1987). Visuo-manual pursuit tracking of human two-dimensional movements. *Journal of Experimental Brain Psychology: Human Perception and Performance, 13*, 62–78.

Viviani, P., & Mounoud, P. (1990). Perceptuomotor compatibility in pursuit tracking of two-dimensional movements. *Journal of Motor Behavior, 22*, 407–443.

Viviani, P., & Stucchi, N. (1989). The effect of movement velocity on form perception: Geometric illusions in dynamic displays. *Perception and Psychophysics, 46*, 266–274.

Viviani, P., & Terzuolo, C. (1982). Trajectory determines movement dynamics. *Neuroscience, 7*, 431–437.

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The influence of robotic guidance on different types of motor timing

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Abstract

Robotic guidance as a means to facilitate motor learning and rehabilitation has received considerable attention during the last few years. However, mixed outcomes suggest that the benefits might be restricted to certain movement characteristics. Here we investigate the effects of robotic guidance on different kinds of motor timing. In particular these were event-based versus emergent timing and absolute versus relative timing. Two groups of participants performed two variants of a circle-drawing task in a synchronization-continuation paradigm. The one variant was continuous circle drawing (emergent timing), the other variant was intermittent circle drawing (event-based timing). Both the total duration of movement cycles (absolute timing) and the relative duration of sub-movements (relative timing) were measured. Half of the participants in each group were guided by a robot device during synchronization (experimental participants), the other half of the participants received no guidance (control participants). Whereas guided participants in both timing-task groups had superior performance during the synchronization phase, during continuation there were no group differences in the continuous timing task anymore. In contrast, with the intermittent timing task experimental participants were more accurate in their relative timing than control participants. These results suggest that relative timing, but not absolute timing, benefits from robotic-guidance training. Possibly those movement characteristics, which are hard to demonstrate visually or verbally, and relative timing in particular, profit from robotic guidance during practice.

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Introduction

Physical guidance serves to assist a person who performs a motor task in order to help him or her to learn it (Schmidt & Lee, 1999), for example in sports, rehabilitation or musical training. A typical form of physical guidance is hand-over-hand assistance that the teacher provides to the student to demonstrate how the movement should be performed. Another, and more recent, possibility is the use of robotic devices to guide movements. In this study we inquire into the effects of a robotic-guidance training (or haptic-guidance training) on different kinds of motor timing.

For a long time the prevalent view has been that physical guidance techniques support the learning of motor skills by way of demonstrating the task and providing a feeling of the correct movement (e.g., Holding, 1970; Holding & Macrae, 1964). Furthermore the techniques reduce errors and hence enable the student to learn a movement in a safe manner, for example by preventing him or her from falling. However, there are also less favourable aspects of physical-guidance techniques, as has been summarized by Schmidt and Lee (1999). They point out that most previous studies of physical guidance investigated the immediate effects on performance, but not on learning, i.e. when the guidance has been removed. They argue that beneficial effects are only temporary and refer to an early study by Armstrong (1970), which showed that guidance leads to almost perfect performance during training, but is not superior to other techniques after it has been removed.

Despite the doubts regarding the effectiveness of physical guidance for learning, during the last few years major efforts have been made to design robotic devices that support human movements and to investigate their effects on performance and learning of both, physically disabled (e.g., Reinkensmeyer, Emken, & Cramer, 2004; Kahn, Zygman, Rymer, & Reinkensmeyer, 2006; Prange, Jannink, Groothuis- Oudshoorn, Hermens, & Ijzerman, 2006; Takahashi, Yeghiaian, Le, Motiwala, & Cramer, 2007; Marchal-Crespo & Reinkensmeyer, 2009) and healthy persons (e.g., Emken & Reinkensmeyer, 2005; Liu, Cramer, & Reinkensmeyer, 2006; Reinkensmeyer & Patton, 2009). Physical guidance by a robotic device rather than by a human therapist or trainer can make the training more precise and consistent and might be more economical. Nevertheless, whereas some studies showed benefits of robotic guidance, other studies showed that robotic guidance does not improve motor learning (cf. Reinkensmeyer & Patton, 2009, for review).

In view of the inconsistent findings, the obvious question is which tasks or task characteristics benefit from robot-supported training and which do not. Most likely tasks differ in their susceptibility to the effects of robotic guidance (Reinkensmeyer, Galvez, Marchal-Crespo, Wolbrecht, & Bobrow, 2007). A first step toward answering the question is based on a distinction between temporal and spatial movement characteristics.

There is some evidence according to which learning of temporal characteristics is particularly susceptible to beneficial effects of haptic guidance (Feygin, Keehner, & Tendick, 2002; Marchal-Crespo & Reinkensmeyer, 2008a; Milot, Marchal-Crespo, Green, Cramer, & Reinkensmeyer, 2010). Acquisition of spatial characteristics, in contrast, may profit more from visual-guidance training (Feygin et al., 2002; Liu et al., 2006).

For example, Marchal-Crespo and Reinkensmeyer (2008a) showed that a haptic-guidance training helped healthy adults to learn how to steer through a virtual environment on a screen. At first glance this seems to require the learning of spatial characteristics. However, when a vehicle, which moves at a certain speed, has to follow a certain path, the proper timing of the movements of the steering wheel represents a major problem. In two experimental groups force was applied to the participant’s hand by a force-feedback steering wheel. Guidance was designed to anticipate turns, i.e., it helped participants to change direction at the right time. The authors compared the performance of the guidance groups with the performance of a control group and could show that experimental participants performed better than controls during both, training and retention. These findings were expanded by Marchal-Crespo, Furumasu, and Reinkensmeyer (2010) who showed that haptic-guidance training improved the steering abilities of healthy children as well as of a disabled child with a severe motor impairment in a real wheelchair.

Other studies that showed positive effects of a robotic-guidance training on learning involved tasks like playing drums (Grindlay, 2008) or a pinball-like game (Milot et al., 2010). These are tasks which critically depend on timing accuracy. For example in the study by Grindlay (2008) different rhythms were presented to the participants, either auditory or haptically, and should be reproduced afterwards with drumsticks. Feygin (2002) compared the performance of a haptic-guidance group with the performance of a visual group and a combined group, which received both, haptic and visual information. Participants learned a complex three-dimensional movement and reproduced it in a test phase. The authors analyzed the movements with measures of spatial and temporal characteristics and showed that haptic guidance alone was better for the learning of the timing, whereas visual training was more beneficial for the learning of spatial characteristics.

Although several studies show positive effects of robotic-guidance training on the learning of temporal aspects of a movement, not all do so. For example, Marchal-Crespo and Reinkensmeyer (2008b) showed that guidance training did not enhance the learning of a pinball-like hitting task compared to unguided training, but was perturbing instead. Participants in this study were not informed as to which trials were guided and which were not, and the authors argue that participants therefore might have relied too much on the guidance, what prevented them from learning. Alternatively, haptic guidance might be beneficial for the learning of certain types of motor timing, but not of others.

Motor timing is not a unitary concept, but different kinds of timing can be distinguished. Thus, inconsistent findings on the effects of robotic guidance could come about because different tasks tap different kinds of timing. The purpose of the present study is to investigate potentially different effects of robotic guidance on different aspects of motor timing. In particular these are event-based versus emergent timing and absolute versus relative timing.

There is a broad agreement in the literature on the distinction between explicit and implicit timing (Zelaznik, Spencer, & Ivry, 2002) or event-based and emergent timing (Ivry, Spencer, Zelaznik, & Diedrichsen, 2002). Event-based (explicit) timing is assumed to depend on an explicit representation of time, whereas emergent (implicit) timing arises as an emergent property of the movement. Zelaznik et al. (2002) refer to the example of a sprinter: first his timing is explicit since he anticipates the start of the run. While running, the timing becomes more and more implicit, and he produces the required durations of sub-movements in an emergent manner.

The notion of distinct timing mechanisms rather than a single general one, as claimed earlier by several authors (e.g., Franz, Zelaznik, & Smith, 1992; Keele & Ivry, 1990; Keele, Pokorny, Corcos, & Ivry, 1985; Treisman, Faulkner, & Naish, 1992; Ivry & Hazeltine, 1995), arose from studies that used tapping, intermittent circle-drawing, and continuous circle-drawing tasks. In these studies, timing variability was correlated between different tapping and intermittent circle-drawing tasks as well as between different continuous circle-drawing tasks. In contrast, the timing variability of continuous circle drawing was not correlated with the timing variability of tapping or intermittent circle drawing (Robertson, Zelaznik, Lantero, Bojczyk, Spencer, Doffin, & Schneidt, 1999; Zelaznik, Spencer, & Doffin, 2000; Zelaznik et al., 2002). These findings led the authors to the assumption that discrete timing tasks such as tapping or intermittent circle drawing rely on explicit timing mechanisms, whereas continuous timing tasks such as consecutive circle drawing invoke mechanisms of emergent timing. Further support for the distinction between event-based and emergent timing comes from neuropsychological studies. Patients with certain cerebral lesions had considerable difficulty in performing discrete timing tasks. In contrast, their ability to perform continuous rhythmic movements was not affected (e.g., Spencer, Zelaznik, Diedrichsen, & Ivry, 2003).

The distinction between emergent and discrete motor timing is related to the broad distinction between continuous/rhythmic and intermittent/discrete movements and the differences between them with respect to control and learning (for an overview see Hogan & Sternad, 2007). The emergent-timing task used in the present experiment is continuous and rhythmic, whereas the event-based timing task is intermittent and discrete. Studies of learning these types of movement suggest that they rely on at least partly distinct mechanisms of control and learning, which should embrace different mechanisms of timing control (e.g., Howard, Ingram, & Wolpert, 2011; Ikegami, Hirashima, Taga, and Nozaki, 2010).

Most of the studies that showed beneficial effects of robotic guidance on the learning of motor timing used timing tasks that were rather discrete in nature in that they required initiating a movement at a certain point in time. In these tasks the timing was primarily event-based, i.e. *when* to turn the steering wheel or joystick, *when* to hit the pinball and *when* to hit the drum pad with the drumstick. The findings suggest that the learning of event-based or explicit motor timing might be particularly susceptible to the beneficial effects of robotic-guidance training. However, the timing in the tests of Feygin et al. (2002) was more of the emergent type. Therefore the present experiment was designed to contrast the effects of robotic guidance on both, event-based and emergent motor timing.

We used a circle-drawing task in two variants for two timing groups. Participants performed either continuous (emergent timing) or intermittent (event-based timing) circle drawing in a synchronization-continuation paradigm, which is commonly used in motor-timing studies (e.g. Robertson et al., 1999; Zelaznik, Spencer, Ivry, Baria, Bloom, Dolansky, Justice, Patterson, & Whetter, 2005; Summers, Maeder, Hiraga, & Alexander, 2008; Repp & Steinman, 2010). In the synchronization phase participants had to synchronize their drawing movements with the pace of a metronome. This phase was a learning phase, in which participants were shown which characteristics the movement should have. In the following continuation phase participants heard no more tones and tried to continue their movements with the same pace. This was a test phase, in which participants reproduced the movement. Half of the participants in each timing group were guided by a haptic device during the synchronization phase, whereas the other half performed the task without haptic guidance. The robot guided the participant's hand on a circular trajectory, either continuously or interrupted by pauses, with the correct timing. However, the force exerted by the device could be overridden by the participant. During continuation none of the participants was guided anymore.

The second distinction between different types of motor timing that we examined with respect to the effects of robotic guidance is the one between absolute and relative timing (Terzuolo & Viviani, 1980; Schmidt, 1985). Absolute timing refers to the overall duration of a movement, whereas relative timing refers to the relative durations of sub-movements. Absolute and relative timing in principle differ in their susceptibility to the effects of different training protocols (e.g. Shea, Lai, Wright, Immink,

& Black, 2001; Wulf, 1995), so that they might also differ in their susceptibility to the effects of haptic guidance.

The correct relative timing is difficult in the intermittent circle-drawing task that we used, but not in the continuous circle-drawing task. Participants have problems with parsing the duration of a movement cycle in circles and pauses of equal length. Instead of producing circles and pauses of equal durations, participants tend to lengthen the relative duration of the movement and to shorten the relative duration of the pause (e.g. Zelaznik et al., 2002). In contrast, with continuous circle drawing the relative durations of successive circles do not systematically differ.

We examined absolute and relative timing by way of analyzing the timing performance in terms of three different measures, two for absolute and one for relative timing. Since it is well known that robotic guidance leads to improved performance during training, we expected the guided groups to be more accurate in absolute timing during the synchronization phase. Relative timing was only relevant in the discrete timing task (intermittent circle drawing), where a movement cycle should be parsed in a circle and a pause of equal length. Therefore an effect regarding relative timing was expected only for the discrete task, but not for the continuous task in which circles were produced without interruptions. However, our main interest was not in the synchronization phase, which primarily served as a learning phase in which the movement was demonstrated to the participants. Rather, we intended to answer the question whether robotic guidance leads to a more accurate absolute and/or relative timing in the continuation phase and thus facilitates learning of either one or both timing tasks.

Methods

Participants

A total of 78 participants volunteered for the study. Their age ranged from 18 to 36 years (M=23.5 years, SD=3.71 years). Forty-four of the participants performed the continuous (emergent) timing task (32 female, 12 male; mean age: 22.9 years). Twenty-two of them (13 female, 9 male; mean age: 22.7 years) were supported by the robot during synchronization (experimental group), whereas 22 participants (19 female, 3 male; mean age: 23.2 years) were in a control group without robotic guidance. The discrete (event-based) timing task was performed by 34 participants (15 female, 19 male; mean age: 24.3 years). Eighteen (7 female, 11 male; mean age: 24.4 years) of them were supported by robotic guidance during synchronization (experimental group), and 16 (8 female, 8 male; mean age: 24.1 years) performed without guidance (control group). All participants were right-handed, had normal or corrected to normal vision and no significant language, motor or neurological dysfunction according to their own declaration. Each participant was paid 10 Euro.

Apparatus

Participants drew with a pen on a digitizer (Wacom Intuos4). Position data were sampled at 100 Hz. The tip of the pen was attached to the end of a robot arm (Phantom Premium 1.5 A, SensAble Technologies). The connecting link at the end of the robot arm carried a hole into which the tip of the pen was inserted (see Fig. 1a). The pen was held there by a minute rubber ring inside the walls of the hole, so that it could be tilted freely in all directions. Only with respect to horizontal movements the link between robot arm and tip of the pen was rigid. The position of the tip of the pen was mapped on the position of a cursor on the monitor, a green marker of 5 mm diameter. To avoid injuries in case the Phantom gets out of control, a safety barrier was placed between it and the participant. Figure 1b shows the whole experimental setup with Phantom, the digitizer and the monitor (Iiyama S902JT VisionMaster Pro 451) which was placed in about 90 cm distance from the participant's eyes.

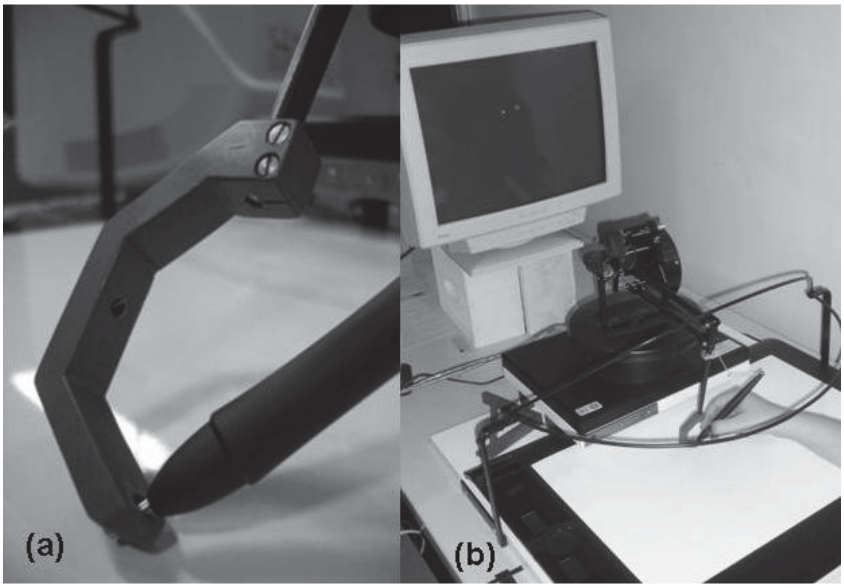

Fig. 1. Apparatus: (a) The tip of the pen was attached to the lower end of the stylus of a Phantom 1.5. (b) Participants were seated in front of a digitizer tablet and faced a monitor.

Design and procedure

We compared the performance of a robotic-guidance (or experimental) group and a control group for two kinds of timing task, a continuous one (emergent timing) and a discrete one (event-based timing). Thus there were four groups of participants in total. Participants were seated in front of the digitizer in a quiet and dimly lit room. They were instructed to watch the screen and wore earphones via which tones were presented and which shielded them from other, distracting auditory stimuli such as the drawing noise.

First the instructions were read and five familiarization trials were performed. During these trials, participants performed either with or without robotic guidance during the synchronization phase, depending on the group they were assigned to. The experiment proper took about one hour and consisted of 57 trials. Each trial consisted of a synchronization phase, in which participants should synchronize their movements with the pace of a metronome that produced a tone of 30 ms duration every 1000 ms, and a continuation phase, in which they should maintain the timing established during synchronization. Participants of the experimental group were informed that the robot would support their movements, and that the guidance would end together with the tones.

Although the focus was on the timing of the participants' movements, there was the additional requirement to draw circles with a diameter of roughly 10 cm. A blue marker was presented on the monitor which indicated the topmost position of the ideal circle where movements should start and end. To illustrate the requested diameter of the circular movement, during the first 5 s of each trial an additional white marker was presented which indicated the lowest position of the ideal circle. The cursor was visible during these first 5 s only.

Continuous timing task

At the start of each trial, participants moved the cursor to the topmost position of the ideal circle (blue marker). After two seconds the first tone appeared, and participants started to draw circles continuously. They tried to synchronize their movements with the pace of the auditory stimulus, i.e., they tried to pass the blue marker every 1000 ms in synchrony with the tone (see Fig 2a). During the synchronization phase the experimental group was assisted by the haptic device. More specifically, at each point in time there was a force field which drove the tip of the pen to a target position on the circumference of a circle with 10 cm diameter; the target position moved around the circumference within 1000 ms. The force was 0.3*d* N, with *d* as the distance in mm of the current position of the tip of the pen from its target position (upper limit: 10 N). The participants of the control group also drew with the pen attached to the Phantom device, but there was no guidance as in the experimental group. Each synchronization phase lasted 16 seconds, i.e. 16 circles. For the following 30 s participants were instructed to continue their movements with an unchanged pace, i.e. they were told to draw circles at the same pace (and with the same diameter) as in the synchronization phase, as if the tones would still appear. After 46 seconds a high-pitched tone was presented and the cursor became visible again. This indicated the end of the trial.

Discrete timing task

The discrete timing task was somewhat different from the continuous task. Instead of drawing circles continuously, participants should pause after each circle (see Fig. 2b). The circles and the pauses should be synchronized with the tones which appeared every 1000 ms. Thus, participants should start a circular movement with the first tone and end at the topmost position in synchrony with the subsequent tone. Then they should pause for 1000 ms until the third tone, in synchrony with which they should start the next circular movement, and so forth. The synchronization phase lasted 16 seconds, so that 8 circles and 8 pauses were produced. Again the experimental group was guided by the robot during this phase, whereas the control group tried to synchronize their movements without any physical support. For the subsequent continuation phase, which lasted another 30 seconds (15 circles + 15 pauses), participants were instructed in the same way as participants who performed the continuous task.

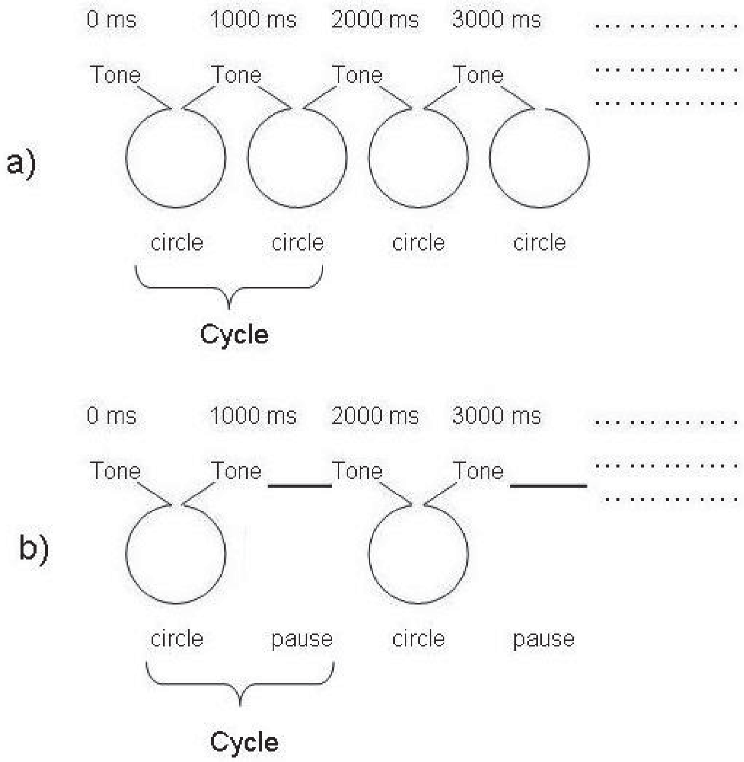

Fig. 2. Timing tasks. With the continuous timing task (a) participants had to draw circles successively and pass the topmost position of the circle in synchrony with the tones. Two circles were merged to one cycle. Participants with the discrete timing task (b) should rest after each circle for 1000 ms. One circle and the following pause were merged to a cycle.

Data analysis

In a first step, the position-time curves were low-pass filtered (fourth-order Butterworth, 5 Hz, dual-pass) and individual circles and pauses were identified for each trial. For this purpose the y-velocity (velocity of the vertical motion of the cursor on the monitor or, equivalently, the forward-backward movement of the hand) was calculated by means of a central-difference algorithm. Subsequently the velocity profile was scanned. For the continuous timing task, a circle was defined as lasting from the one zero crossing to the one after the next, which is equivalent to the time from the beginning of a downward motion of the cursor to the beginning of the next one. For the discrete timing task, a circle was defined to last from the time at which downward velocity exceeded a threshold of 20 mm/s for at least 15 successive samples to the last time at which upward velocity was larger than a threshold of 20 mm/s for the preceding 15 samples or longer. A pause was defined to last from the end of one circle to the start of the subsequent one. (As a consequence of the use of the velocity thresholds unequal zero, relative durations of pauses should tend to be overestimated rather than underestimated.)

For the analysis pairs of consecutive circles (continuous timing task) or of circles and the subsequent pauses (discrete timing task) were combined to cycles (cf. Figure 2). In the case of an unequal number of circles and pauses in the synchronization or continuation phase of the discrete timing task or an odd number of circles in the synchronization or continuation phase of the continuous task, the last circle in the respective phase was neglected. In addition first and last cycles of synchronization and continuation phases were discarded, and so were deviant cycles that did not meet the following criteria: first, the cycle had a duration between 1.5 and 2.5 s, second, the Euclidean distance between the start and the final position of the cursor was not larger than 25 mm, third, start and end position of the cycle had a y-position above the mean y-position of the whole cycle, and fourth, the second part of the cycle had a duration longer than zero.

For the cycles of the synchronization phase and the continuation phase of each trial the constant error, i.e., the mean difference between requested cycle duration (2000 ms) and the actual cycle durations, was calculated and served as a measure of absolute-timing accuracy. This measure in particular indicates systematic decelerations or accelerations in the continuation phase. As an additional (and more frequently used) measure of absolute-timing accuracy the variable error was determined, i.e., the standard deviation of the cycle durations in each phase of each trial. The mean difference between the durations of the first parts of the cycles (circles) and the durations of the second parts of the cycles (circles or pauses) served as a measure of relative-timing accuracy, again computed separately for the synchronization phase and continuation phase of each trial. Since each component ideally lasted 1000 ms, this measure should be around zero when participant’s relative timing was accurate. In contrast, this measure was above zero when the duration of the first part of the cycle was longer than the duration of the second part, and below zero when the second part took longer.

The three dependent variables for each of the 57 trials were averaged to form means for 3 blocks of 19 trials each. The individual means for each block were entered in the statistical analyses. Three-way ANOVAs were run, separately for the synchronization and continuation phase. Timing task (continuous vs. discrete) as well as guidance condition (guided vs. unguided) served as between-participant factors and block as the within-participant factor. Greenhouse-Geisser corrections were applied when appropriate, but the uncorrected degrees of freedom are reported together with the Greenhouse-Geisser epsilon. Effect sizes are given as partial eta-squared.

Results

The results will be reported first for the synchronization phase and thereafter for the continuation phase. The former reflect the immediate performance effects of the robot assistance, whereas the latter reflect the learning effects. The means of the three dependent variables during both synchronization and continuation are shown in Figure 3.

Synchronization phase

In the synchronization phase 4.8 % of all cycles were excluded from analysis (group continuous, guided: 1.5 %, group continuous, unguided: 7.4 %, group discrete, guided: 5.1 %, group discrete, unguided: 5.2 %).

As expected, absolute timing was more accurate, i.e., the mean deviation of cycle durations from 2000 ms was closer to zero and the standard deviation of cycle durations was smaller, when participants were guided by the robot than in the unguided control group. This was true for both timing tasks, continuous (emergent timing) and discrete (event-based timing). The variable timing error of the discrete task was in general higher than that of the continuous task. In contrast, with respect to relative timing only participants in the two groups with the discrete task-with and without haptic guidance-differed.

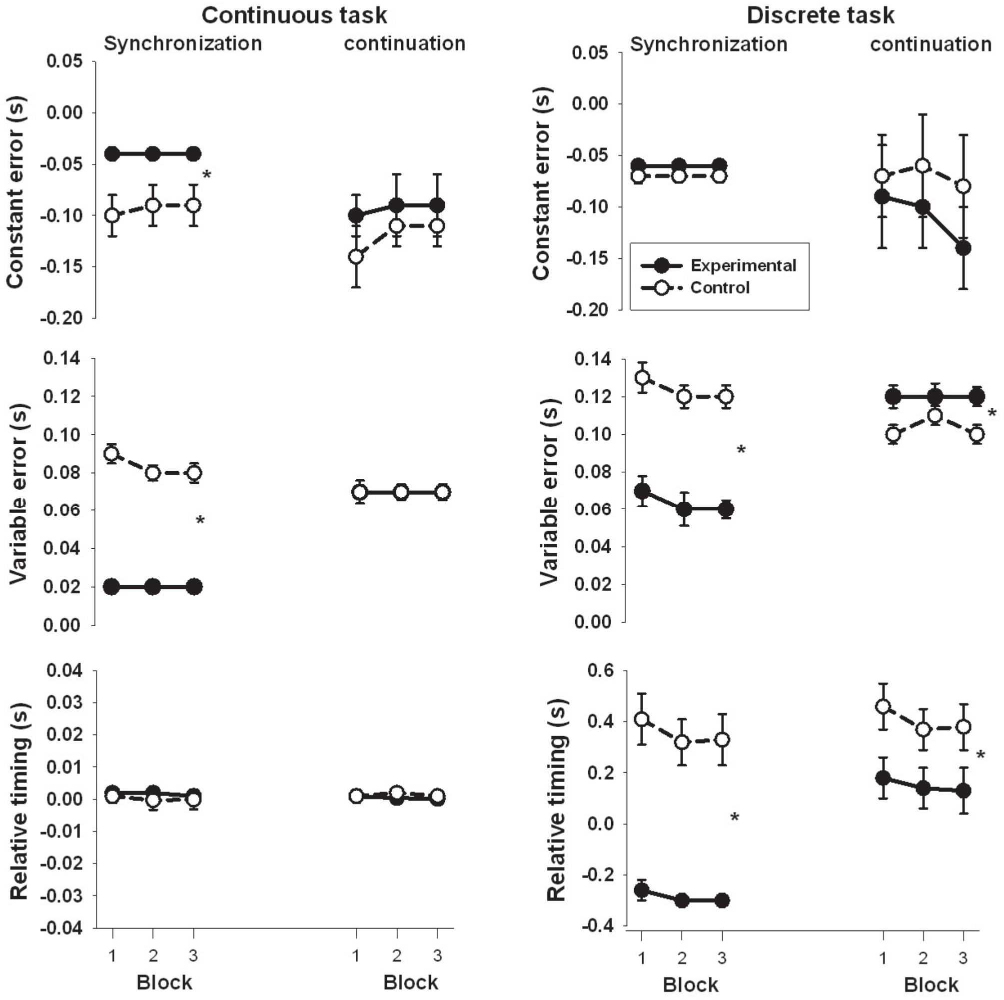

Fig. 3. Constant error of cycle duration (top), variable error of cycle duration (centre), and relative timing (bottom) during the synchronization and the continuation phase for the continuous (left) and the discrete (right) timing task and the 3 blocks of trials in each phase. Standard errors are given as vertical bars. An asterisk close to the lines indicates a significant difference between the experimental (guided) and the control (unguided) participants.

The ANOVA of the constant error of absolute timing revealed a significant difference between guidance conditions, F(1,74) = 7.24, $p<.01$, $\eta_p^2 = .09$, as well as a significant interaction of the factors timing task and guidance condition, F(1,74) = 5.33, $p = .02$, $\eta_p^2 = .07$. Performance improved significantly across blocks, F(2,148) = 3.54, $p = .05$, $\varepsilon = .67$, $\eta_p^2 = .05$, but there was no significant interaction of blocks with timing task or guidance condition. Further analyses that were performed separately for the two timing-task groups revealed that experimental (guided) participants performed significantly better than control (unguided) participants with the continuous task, F(1,42) = 8.57, $p <. 01$, $\eta_p^2 = .17$, whereas the difference between these two groups with the discrete task failed to reach statistical significance, F(1,32) = 0.58, $p = .45$, $\eta_p^2 = .02$.

The ANOVA of the variable timing error revealed significant main effects of the factors timing task, F(1,74) = 70.72, $p < .01$, $\eta_p^2 = .49$, and guidance condition, F(1,74) = 157.10, $p < .01$, $\eta_p^2 = .68$. Performance improved across blocks, F(2,148) = 6.06, $p < .01$, $\varepsilon = .98$, $\eta_p^2 = .08$. Separate ANOVAs for the two timing-task groups showed that with both tasks, continuous, F(1,42) = 200.05, $p < .01$, $\eta_p^2 = .83$, and discrete, F(1,32) = 38.58, $p < .01$, $\eta_p^2 = .55$, participants had a significantly smaller variability of the cycle durations when they were supported by the robot.

Regarding relative timing, the overall ANOVA revealed a significant main effect of the factor guidance condition, F(1,74) = 65.86, $p < .01$, $\eta_p^2 = .47$, as well as a significant interaction of timing task and guidance condition, F(1,74) = 66.44, $p < .01$, $\eta_p^2 = .47$. Relative timing did not change significantly across blocks, and there was no significant interaction involving this factor. Separate analyses for the two timing-task groups showed that participants with the discrete task were significantly more accurate when they were supported by the robot, F(1,32) = 50.70, $p < .01$, $\eta_p^2 = .61$, than in the unsupported control condition. With the continuous task, in contrast, participants of the experimental and control groups did not differ significantly in their relative-timing performance, F<1. The difference between the durations of the first and second circles of each cycle was close to zero in both the experimental (guided) and control (unguided) condition.

Continuation phase

In the continuation phase 8.7 % of all cycles were excluded from analysis (group continuous, guided: 5.7 %, group continuous, unguided: 7.6 %, group discrete, guided: 14.4 %, group discrete, unguided: 8.1 %).

The analysis of the timing performance in the continuation phase reveals whether experimental (guided) participants could maintain their superior performance after the robot has been switched off. As soon as the guidance has been removed, there was no more difference between the guidance conditions regarding the constant error of absolute timing, neither with the continuous nor with the discrete task. Participants in the two groups with the continuous timing task did also not differ regarding the variable error of absolute timing and relative-timing accuracy. In contrast, experimental participants with the discrete timing task were more accurate in their relative timing than unguided control participants, but also more variable in their absolute timing.

The ANOVA of the constant error showed no significant main effects, neither for the factor timing task nor for the factor guidance condition, and the interaction of these two factors was also not significant. The change across blocks failed to reach statistical significance, but there was a significant block x timing task interaction, F(2,148) = 4.88, $p = .01$, $\varepsilon = .84$, $\eta_p^2 = .06$. Separate analyses of the two timing-task groups showed that this interaction was due to a marginally significant improvement of performance with the continuous task, F(2,84) = 2.67, $p = .09$, $\varepsilon = .75$, $\eta_p^2 = .06$, and a decline of performance across blocks with the discrete task, F(2,64) = 3.66, $p = .04$, $\varepsilon = .82$, $\eta_p^2 = .10$. The decline of absolute timing performance resulted from a progressive reduction of the mean cycle duration. The interaction between block and guidance condition was not significant.

For the variability of cycle duration, the main effect of timing task, F(1,74) = 106.47, $p < .01$, $\eta_p^2 = .59$, and the timing task x guidance condition interaction, F(1,74) = 4.10, $p = .05$, $\eta_p^2 = .05$, were significant. The variable timing error did not change significantly across blocks. Separate analyses revealed that there was no difference between experimental and control participants in the continuous timing-task group, $F<1$. In contrast, with the discrete task the variable timing error was significantly larger for participants who were trained with the robot than for control participants, F(1,32) = 5.36, $p = .03$, $\eta_p^2 = .14$.

Regarding the difference between the durations of the first part of the cycle and the second part (relative timing), in the continuation phase there were still significant effects of the factors timing task, F(1,74) = 28.22, $p < .01$, $\eta_p^2 = .28$, and guidance condition, F(1,74) = 6.04, $p = .02$, $\eta_p^2 = .08$, as well as a significant interaction of these two factors, F(1,74) = 5.96, $p = .02$, $\eta_p^2 = .08$. The factor block, F(2,148) = 4.86, $p = .02$, $\varepsilon = .67$, $\eta_p^2 = .06$, as well as the block x timing task interaction, F(2,148) = 4.75, $p = .02$, $\varepsilon = .67$, $\eta_p^2 = .06$, also reached statistical significance. Separate ANOVAs for the two timing-task groups showed that the significant main effect of guidance condition was due to the superiority of the guidance group with the discrete timing task. Participants who had been guided by the robot in the synchronization phase were still significantly more accurate in their relative timing in the continuation phase, F(1,32) = 4.59, p = .04, η_p^2 = .13, even though their performance now was also biased in that their circles were too long and their pauses too short. All participants in the discrete timing-task group improved significantly across blocks, F(2,64) = 3.69, p = .05, ε = .67, η_p^2 = .10. With the continuous timing task, experimental participants did not differ from control participants in their relative timing, F(1,42) = 1.45, p = .24, η_p^2 = .03. Both groups had mean differences around zero, which indicates that first and second circles of each cycle were of equal mean durations.

Discussion

In this study we investigated the effects of robotic guidance on the performance and learning of different types of motor timing in a synchronization-continuation paradigm. Two different timing tasks, continuous and discrete, served to distinguish between two different timing mechanisms, emergent and event-based timing (e.g., Zelaznik et al., 2002). We used three different measures to assess performance both with respect to absolute and relative timing (e.g., Terzuolo & Viviani, 1980).

In the synchronization phase, where participants synchronized their movements with the pace of a metronome, participants with the continuous timing task, who were supported by the robot, showed a more accurate performance in absolute timing than the control group without robot support, i.e., the robot helped them to produce each cycle with the exact target duration. This resulted in cycle durations of approximately two seconds as well as a small variability. For the continuous task there was no difference between the groups with and without robot guidance regarding the relative timing, i.e., the relation between the durations of the first and the second circle of each cycle. This is not surprising since the correct relative timing was not an inherent difficulty of the continuous timing task which tapped the emergent timing mechanism.

Experimental (guided) participants with the discrete timing task were more accurate during synchronization in all three dependent measures than control (unguided) participants, although for the constant error of absolute timing the difference failed to reach statistical significance. Participants in the experimental condition profited from the robot in that it helped them to keep the duration of the circle and the pause of each cycle more similar. In summary, the results of the synchronization phase are consistent with previous observations that robotic guidance leads to better timing performance during practice (Marchal-Crespo & Reinkensmeyer, 2008a; Reinkensmeyer & Patton, 2009; Schmidt & Lee, 1999).

The more important question is whether the benefits of haptic guidance persist in the continuation phase, after the robot has been switched off. This was the case only for the relative-timing performance of the discrete task: participants who had been guided by the robot during synchronization were more accurate in keeping the duration of the circle and the pause similar than participants of the control group. In contrast, experimental participants with the continuous task did not differ from the control participants in any of the measures anymore.

Besides the improvement of the relative timing, experimental participants with the discrete timing task also showed increased variability of their absolute timing. Most likely this increase of the variable error of absolute timing is a consequence of the better relative timing rather than a genuine detrimental effect of the robot training. Experimental participants made longer pauses than control participants, as indicated by the relative-timing measure. Since the timing variability commonly increases with increasing interval duration (e.g. Peters, 1989), it is feasible that the larger variable error of absolute timing in the experimental group reflects a higher variability of pause durations which in turn result from longer pauses.

To test this hypothesis, we computed the regression of the individual variable errors of absolute timing on the individual measures of relative timing, with both variables averaged across blocks of trials. The scatter plot is shown in Figure 4. The slope of the linear regression was significant, -.02 (95% confidence interval: -.04 to 0), that is, the variable error of absolute timing did indeed increase with increasing relative-timing accuracy (i.e., increasing pause durations).

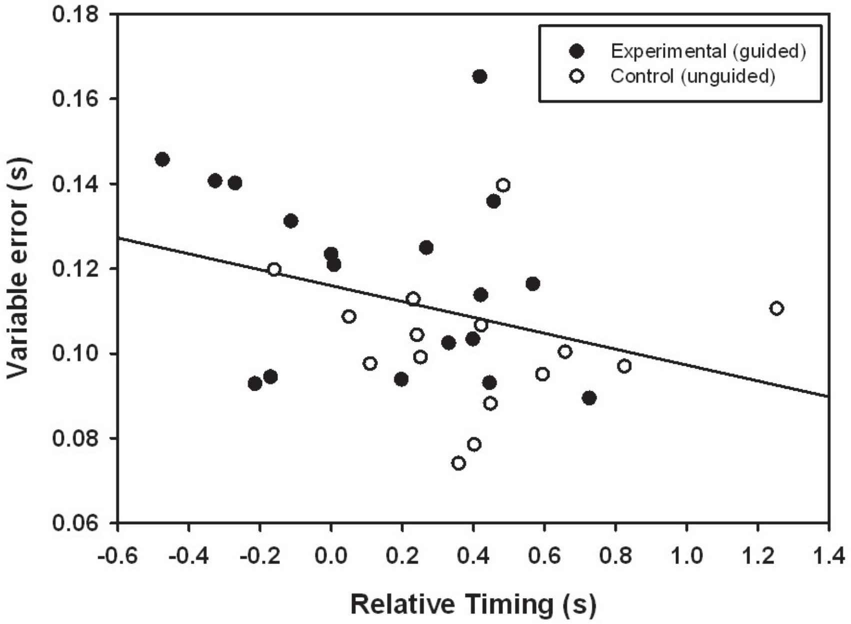

Fig. 4. Scatter plot of variable error as a function of relative timing in the two groups with the discrete timing task. Both variable error and relative timing are averages across the three blocks of trials for each individual participant.

Overall the residuals of the variable timing error sum up to zero. However, in the two groups with the discrete timing task they could be different. They were .005 and -.006 s in the experimental and the control group, respectively. Even though the variable errors of the experimental group were preferably above the regression line and those of the control group below (cf. Figure 4), the difference was not statistically significant, t(32)=1.66, p=.11. Thus, for (statistically) equivalent relative-timing accuracy the absolute-timing variability was not significantly different in the two groups. Therefore the higher cycle variability of the participants of the experimental group is primarily due to their more accurate relative timing.

Why did robotic guidance facilitate the learning of relative timing only? Perhaps relative timing per se profits more from robotic-guidance training than absolute timing. Relative timing was also an important aspect in the study of Feygin et al. (2002) and in other studies (Grindlay, 2008; Marchal-Crespo & Reinkensmeyer, 2008a; Marchal-Crespo & Reinkensmeyer, 2010; Milot et al., 2010), in which positive effects of guidance on the learning of temporal movement characteristics could be shown. Since learning of a correct relative timing in our study was required only in the discrete timing task, but not in the continuous task, where circles were drawn consecutively and the relative timing of successive circles was correct from the very start, the present data do not allow any conclusion with regard to the learning of relative timing in a continuous timing task.

In spite of the rather consistent findings, one may doubt that relative timing per se is crucial for the benefit of robotic-guidance training. Perhaps it is not the kind of timing, but the difficulty of communicating or instructing certain movement characteristics that determines whether their learning profits from robotic guidance. Some movements or movement characteristics can be taught easily by verbal instruction or visual demonstration. In contrast, others are hard to explain and to communicate without producing the movement, but can easily be demonstrated by guiding the learner. The continuous and discrete timing tasks in our experiment differed with regard to this aspect. Whereas the instructions for the continuous circle-drawing task were easy to understand, it was more difficult to explain verbally when to draw and rest during the intermittent circle-drawing task. The results are in accordance with this hypothesis, since participants who practiced the discrete timing task had obvious difficulties with parsing the cycles in circles and pauses of equal durations (see Fig. 3).

Such considerations suggest that the learning of those movements or movement characteristics will benefit from robotic guidance which are otherwise hard to communicate. Temporal aspects are in general harder to demonstrate verbally or visually than spatial characteristics. When and how to move to play the drums (Grindlay, 2008) or the pinball (Milot et al., 2010), to turn a steering wheel (Marchal-Crespo & Reinkensmeyer 2008a; Marchal-Crespo & Reinkensmeyer, 2010) or how to make a movement with a certain spatio-temporal pattern (Feygin et al., 2002) is hard to explain, but easier to demonstrate haptically. Perhaps this is why these kinds of movements are more likely to profit from haptic guidance. Further experiments with different timing tasks are needed to clarify the question if it is really the temporal aspect or a certain mode of timing that makes a task susceptible to the beneficial effects of robotic guidance or if it is rather the difficulty of demonstration that is crucial.

Finally, we want to briefly address the reasons for the phenomenon which can also be found in previous studies of intermittent circle drawing (e.g., Zelaznik et al., 2002), namely the tendency of participants to draw circles that are too long in duration and to make pauses that are too short. The control group showed this behaviour from the beginning and throughout the whole experiment, during synchronization as well as during continuation. Performance of the experimental participants was biased in the same direction as soon as the robot was switched off, even though not to the extent as the performance of the control participants was.

The different relative durations of circles and pauses might be due to differences in time perception during drawing a circle and pausing. Several studies (e.g., Chaston & Kingstone, 2004) demonstrate that time seems to pass faster when a task is performed. According to the attentional model of prospective time estimation (Thomas & Weaver, 1975), attention has to be shared between a timer and additional information. This timer produces pulses with a particular frequency that are accumulated and used for time estimation. When attention is distracted from the timer, pulses are lost and time is underestimated. Applied to the task in our experiment, the time interval during drawing the circle might have been perceived as shorter than it really is, since the drawing task distracts attention. Zelaznik et al. (2002) explained the larger variability of the cycle components than of the overall duration as resulting from the primary goal of maintaining the overall period; they refer to a study by Billon, Semjen, and Stelmach (1996) who argue that the action is represented in a hierarchical manner, with maintaining the overall period as the primary goal and maintaining the subintervals as subordinate goals. According to this reasoning, participants in our experiment might have made the short pauses in order to compensate for the long circle durations to keep the overall period of two seconds.

References

Armstrong, T. R. (1970). Feedback and perceptual-motor skill learning: A review of information feedback and manual guidance training techniques. Tech. Rep. No. 25. Ann Arbor: University of Michigan, Department of Psychology.

Billon, M., Semjen, A., & Stelmach, G. E. (1996). The timing effects of accent production in periodic finger-tapping sequences. *Journal of Motor Behavior, 28,* 198-210.

Chaston, A., & Kingstone, A. (2004). Time estimation: The effect of cortically mediated attention. *Brain and Cognition, 55,* 286-289.

Emken, J. L., & Reinkensmeyer, D. J. (2005). Robot-enhanced motor learning: Accelerating internal model formation during locomotion by transient dynamic amplification. *IEEE Transactions on Neural Systems and Rehabilitation Engineering, 13,* 33-39.

Feygin, D., Keehner, M., & Tendick, F. (2002). Haptic guidance: Experimental evaluation of haptic training method for a perceptual motor skill. *Proceedings of 10th International Symposium on Haptic Interfaces for Virtual Environment and teleoperator Systems (Haptics 2002)*, 40-47.

Franz, E. A., Zelaznik, H. N., & Smith, A. (1992). Evidence of common timing processes in the control of manual, orofacial, and speech movement. *Journal of Motor Behavior*, *24,* 281-287.

Grindlay, G. (2008). Haptic guidance benefits musical motor learning. *Proceedings of Symposium on Haptic interfaces for Virtual Environment and Teleoperator Systems*, 397-404.

Hogan, N., & Sternad, D. (2007). On rhythmic and discrete movements: reflections, definitions and implications for motor control. *Experimental Brain Research, 181, 13-30.*

Holding, D. H. (1970). Learning without errors. In L. E. Smith (Ed.), *Psychology of motor learning (pp. 59-74)*. Chicago: Athletic Institute.

Holding, D. H., & Macrae, A. W (1964). Guidance, restriction and knowledge of results. *Ergonomics, 7,* 289-295.

Howard, I. S., Ingram, J. N., & Wolpert, D. M. (2011). Separate representations of dynamics in rhythmic and discrete movements: evidence from motor learning. *Journal of Neurophysiology, 105, 1722-1731.*

Ikegami, T., Hirashima, M., Taga, G., & Nozaki, D. (2010). Asymmetric transfer of visuomotor learning between discrete and rhythmic movements: *The Journal of Neuroscience, 30, 4515-4521.*

Ivry, R. B., & Hazeltine, R. E. (1995). Perception and production of temporal intervals across a range of durations: Evidence for a common timing mechanism. *Journal of Experimental Psychology: Human Perception and Performance, 21,* 3-18.

Ivry, R. B., Spencer, R. M., Zelaznik, H. N., & Diedrichsen, J. (2002). The cerebellum and event timing. In S. M. Highstein & W. T. Thach (Eds.), *The cerebellum: Recent developments in cerebellar research* (Vol. 978, pp. 302-317). New York: New York Acadamy of Sciences.

Kahn, L. E., Zygman, M. L., Rymer, W. Z., & Reinkensmeyer, D. J. (2006). Robot assisted reaching exercise promotes arm movement recovery in chronic hemiparetic stroke: a randomized controlled pilot study. *Journal of NeuroEngineering and Rehabilitation, 3.*

Keele, S. W., & Ivry, R. B. (1990). Does the cerebellum provide a common computation for diverse tasks? *Annals of the New York Academy of Sciences, 608,* 179-211.

Keele, S. W., Pokorny, R.; Corcos, D., & Ivry, R. B. (1985). Do perception and motor production share common timing mechanisms? *Acta Psychologica, 60*, 173-193.

Liu, J., Cramer, S. C., & Reinkensmeyer, D. J. (2006). Learning to perform a new movement with robotic assistance: comparison of haptic guidance and visual demonstration. *Journal of NeuroEngineering and Rehabilitation, 3.*

Marchal-Crespo, L., & Reinkensmeyer, D. J. (2008a). Haptic guidance can improve motor learning of a steering task*. Journal of Motor Behavior, 40,* 545-556.

Marchal-Crespo, L., & Reinkensmeyer, D. J. (2008b). Effect of robotic guidance on motor learning of a timing task. *Proceedings of the 2nd Biennial IEEE/RAS-EMBS International Conference on Biomedical Robotics and Biomechatronics*, 199-204.

Marchal-Crespo, L., & Reinkensmeyer, D. J. (2009). Review of control strategies for robotic movement training after neurologic injury. *Journal of NeuroEngineering and Rehabilitation, 6.*

Marchal-Crespo, L., Furumasu, J., & Reinkensmeyer, D. J. (2010). A robotic wheelchair trainer: design overview and a feasibility study. *Journal of NeuroEngineering and Rehabilitation, 7.*

Milot, M.-H., Marchal-Crespo, L., Green, C. S., Cramer, S. C., & Reinkensmeyer, D. J. (2010). Comparison of error-amplification and haptic guidance training techniques for learning of a timing-based motor task by healthy individuals*. Experimental Brain Research, 201,* 119-131.

Peters, M. (1989). The relationship between variability of intertap intervals and interval duration. *Psychological Research*, *51*, 38-42.

Prange, G. P., Jannink, M. J., Groothuis-Oudshoorn, C. G., Hermens, H., & Ijzerman, M. J. (2006). Systematic review of the effect of robot-aided therapy on recovery of the hemiparetic arm after stroke. *Journal of Rehabilitation Research & Development, 43,* 171-184.

Reinkensmeyer, D. J., Emken, J. K., & Cramer, S. C. (2004). Robotics, motor learning, and neurological recovery. *Annual Review of Biomedical Engineering, 6*, 497-525.

Reinkensmeyer, D. J., Galvez, J. A., Marchal-Crespo, L., Wolbrecht, E. T., & Bobrow, J. E. (2007). Some key problems for robot-assisted movement therapy research: a perspective from the University of California at Irvine. *Proceedings of the 2007 IEEE International Conference on Rehabilitation Robotics,* 1009-1025*.*

Reinkensmeyer, D. J., & Patton, J. L. (2009). Can robots help the learning of skilled actions? *Exercise and Sport Sciences Reviews, 37,* 43-51.

Repp, B. H., & Steinman, S. R. (2010). Simultaneous event-based and emergent timing: Synchronization, continuation, and phase correction*. Journal of Motor Behavior, 42,* 11-126.

Robertson, S. D., Zelaznik, H. N., Lantero, D. A., Bojczyk, K. D., Spencer, R. M., Doffin, J. G., & Schneidt, T. (1999). Correlations for timing consistency among tapping and drawing tasks: evidence against a single timing process for motor control. *Journal of Experimental Psychology: Human Perception and Performance, 25*, 1316-1330.

Schmidt, R. A. (1985). The search for invariance in skilled movement behavior. *Research Quarterly for Exercise and Sport, 56*, 188-200

Schmidt, R. A., & Lee, T. D. (1999). Motor control and learning-a behavioral emphasis (3rd ed.) (pp. 316-317). Champaign, IL: Human Kinetics

Shea, C. H., Lai, Q., Wright, D. L., Immink, M., & Black, C. (2001). Consistent and variable practice conditions: effects on relative and absolute timing. *Journal of Motor Behavior, 33,* 139-152.

Spencer, R. M., Zelaznik, H. N., Diedrichsen, J., & Ivry, R., B. (2003). Disrupted timing of discontinuous but not continuous movements by cerebellar lesions. *Science, 300*, 1437-1439.

Summers, J. J., Maeder, S., Hiraga, C. Y., & Alexander, J. R. M. (2008). Coordination dynamics and attentional costs of continuous and discontinuous bimanual circle drawing movements. *Human Movement Science, 27*, 823-837.

Takahashi, C. D., Yeghiaian, L., Le, V., Motiwala, R. R., & Cramer, S. C (2007). Robot based hand motor therapy after stroke. *Brain, 131*, 425-437.

Terzuolo, C. A. & Viviani, P. (1980). Determinants and characteristics of motor patterns used for typing. *Neuroscience, 5*, 1085-1103.

Thomas, E. A. C., & Weaver, W. B. (1975). Cognitive processing and time perception. *Perception & Psychophysics, 17,* 363-367.

Treisman, M., Faulkner, A., & Naish, P. L. (1992). On the relation between time perception and the timing of motor action: evidence for a temporal oscillator controlling the timing of movement. *Quarterly Journal of Experimental Psychology*, *45*, 235-263.

Wulf, G. (1995). Lernen von generalisierten motorischen Programmen und Bewegungsparametern. In L. Jäncke & H. Heuer (Eds.), *Interdisziplinäre Bewegungsforschung* (pp. 498-537). Lengerich: Pabst.

Zelaznik, H. N., Spencer, R. M., & Doffin, J. G. (2000).Temporal precision in tapping and circle drawing movements at preferred rates is not correlated: Further evidence against timing as a general-purpose ability. *Journal of Motor Behavior, 32,* 193-199.

Zelaznik, H., Spencer, R. M., & Ivry, R. B. (2002). Dissociation of explicit and implicit timing in repetitive tapping and drawing movements. *Journal of Experimental Psychology: Human Perception and Performance, 28,* 575-588.

Zelaznik, H. N., Spencer, R. M., Ivry, R. B., Baria, A., Bloom, M., Dolansky, L., Justice, S., Patterson, K., & Whetter, E. (2005) Timing variability in circle drawing and tapping: probing the relationship between event and emergent timing. *Journal of Motor Behavior, 37,* 395-403.

Robotic guidance benefits the learning of dynamic, but not of spatial movement characteristics

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Abstract

Robotic guidance is an engineered form of haptic-guidance training and intended to enhance motor learning in rehabilitation, surgery, and sports. However, its benefits (and pitfalls) are still debated. Here we investigate the effects of different presentation modes on the reproduction of a spatio-temporal movement pattern. In three different groups of participants, the movement was demonstrated in three different modalities, namely visual, haptic, and visuo-haptic. After demonstration participants had to reproduce the movement in two alternating recall conditions, haptic and visuo-haptic. Performance of the three groups during recall was compared with regard to spatial and dynamic movement characteristics. After haptic presentation, participants showed superior dynamic accuracy, whereas after visual presentation participants performed better with regard to spatial accuracy. Added visual feedback during recall always led to enhanced performance, independent of the movement characteristic and the presentation modality. These findings substantiate the different benefits of different presentation modes for different movement characteristics. In particular, robotic guidance is beneficial for the learning of dynamic, but not of spatial movement characteristics.

Introduction

In the last ten to fifteen years professionals from various disciplines such as kinesiology, engineering, neurocognition, psychology, and medicine have an increasing interest in developing new technologies and paradigms to enhance motor learning in surgery, sports, musical training, and rehabilitation. One of these paradigms is robotic guidance. This is an engineered form of haptic guidance, in which a teacher or therapist, for example, provides a hand-over-hand assistance to the student or patient (e.g. Gillespie, Brent, O'Modhrain, Tang, Zaretzky, & Pham 1998). In comparison to human trainers and therapists robots are more consistent and precise (Solis, Avizzano, & Bergamesco 2002) and also less expensive in the long run (Liu, Cramer, & Reinkensmeyer 2006). However, they must not be more effective. Although many studies with patients as well as with healthy persons have been conducted, the effects of such training are not yet well established. There is a strong demand to identify tasks and movement characteristics that actually profit from robotic guidance (for an overview see Reinkensmeyer, Galvez, Marchal, Wolbrecht, & Bobrow 2007, or Reinkensmeyer & Patton 2009). The present study was designed to gain further insight into the effects of a robotic-guidance training on the short-term learning of spatial and dynamic characteristics of a spatio-temporal motor pattern.

In therapy and rehabilitation, robotic guidance is mainly used to facilitate motor recovery after stroke or spinal cord injury (for an overview see Marchal-Crespo & Reinkensmeyer 2009 or Reinkensmeyer, Emken, & Cramer 2004). Robots that guide movements of the upper extremity such as pointing, grasping, reaching, and drawing as well as devices that assist gait training by providing body weight support and guidance of the legs have been tested in clinical studies with patients. Whereas several of these studies indicated that robotic-guidance training can indeed facilitate recovery, others could not show any benefit.

Early research with healthy humans on different kinds of guidance (e.g. Holding 1970; Holding, & Macrae 1964) showed that haptic guidance can demonstrate the task and provide a feeling of the correct movement (that could otherwise not be achieved). However, there have also been early doubts about the endurance of performance. Schmidt and Lee (1999) argue that haptic guidance does indeed support motor performance during training, but is not necessarily superior to other training techniques for learning. They refer to an early study of Armstrong (1970), which showed that guidance leads to almost perfect performance during training, but is not superior to other techniques after it has been removed.

This pessimistic stance has been somewhat ameliorated by more recent studies. Robotic guidance has been used to train to steer a wheelchair (Marchal-Crespo & Reinkensmeyer 2008; Marchal-Crespo, Furumasu, & Reinkensmeyer 2010), to play drums (Grindlay 2008), to write foreign characters (Henmi & Yoshikawa 1998; Solis et al. 2002; Teo, Burdet, & Lim 2002; Palluel-Germain, Bara, Hennion, Gouagout, & Gentaz 2006, 2007), to play a pinball-like game (Marchal-Crespo & Reinkensmeyer 2008; Milot, Marchal-Crespo, Green, Cramer, & Reinkensmeyer 2010) or to produce movements with a certain spatio-temporal pattern (Feygin, Keehner, & Tendick 2002; Liu et al. 2006; Lüttgen & Heuer in press; Lüttgen & Heuer submitted). The guidance that was used in these studies was either guidance in position (HGP) or guidance in force (HGF). The former uses spatial coordinates whereas the latter plays back forces that have previously generated and recorded by an expert (for an overview see Bluteau, Coquillart, Payan & Gentaz 2008).

Many of the studies that investigated the effects of robotic guidance on motor learning could show that this kind of training provides indeed some benefit in comparison to other demonstration modalities, but not all did so (Marchal-Crespo & Reinkensmeyer 2008). Most importantly, it is not well defined which movement characteristics benefit from robotic-guidance training and which do not.

However, there is tentative evidence for the hypothesis that the learning of dynamic movement characteristics, such as timing and velocity profiles, might benefit more from robotic guidance than the learning of spatial movement characteristics. Some authors (e.g., Liu et al. 2006) argue that vision is more accurate for spatial characteristics, the learning of which might thus profit more from visual than from haptic demonstration. In contrast, proprioception might be more accurate for dynamic aspects (e.g. Reinkensmeyer et al. 2009). Consistent with the hypothesis that learning of dynamic movement characteristics is particularly susceptible to robotic guidance, mainly those studies could confirm a beneficial effect of a robotic-guidance training in which dynamic movement characteristics were crucial for performance. Examples are when to turn a steering wheel (Marchal-Crespo & Reinkensmeyer 2008; Marchal-Crespo, Furumasu, and Reinkensmeyer 2010) or when to hit a pinball (Milot, Marchal-Crespo, Green, Cramer, & Reinkensmeyer 2010). In addition positive effects of robotic guidance on velocity accuracy when learning to play a rhythmic sequence with drumsticks (Grindlay 2008) and on the accuracy of a non-natural modulation of velocity during circle drawing (Lüttgen & Heuer in press) could be shown.

The present study was designed to gain further insight into the effects of different demonstration modes on the learning of dynamic and spatial aspects of a drawing movement. The only study known to us that explicitly compared the effects of visual, haptic and visuo-haptic demonstrations on the learning of both, spatial and dynamic aspects, is the one of Feygin et al. (2002). Participants in that experiment learned a complex three-dimensional movement in one of the three different demonstration conditions. In addition there were two recall conditions, haptic and visuo-haptic. Performance was analyzed regarding both, spatial and temporal accuracy. The authors could show that visual training alone was better for the learning of the position and the shape of the movement, whereas haptic guidance alone was better for the learning of dynamic aspects. The combined training led to a performance regarding shape similar to the performance in the visual condition and a performance regarding timing similar to the one in the haptic condition.

Feygin et al. (2002) used a within-participant design, which means that all participants were trained in all conditions. Such a design is problematic for a learning experiment, since transfer effects cannot entirely be excluded (Krauth 1995; Poulton & Freeman 1966). Furthermore, Feygin et al. emphasized spatial accuracy of the movements. For dynamic accuracy they only used a single measure of total-duration accuracy and did not differentiate between different aspects of timing (cf. Lüttgen & Heuer submitted). Thus the results of this study need confirmation and elaboration. Therefore we conducted a similar experiment, but with a between-participant design and a more detailed analysis of dynamic movement characteristics. We tested the effects of visual, haptic, and visuo-haptic demonstration on the short-term learning of different spatial and dynamic aspects of a movement. As in the study of Feygin et al. (2002) we used a position-based guidance method. The learning of dynamic aspects was expected to be superior under the haptic-demonstration condition, whereas the learning of spatial aspects was expected to be superior under the visual-demonstration condition.

Recall was assessed under two conditions, namely haptic feedback only and visuo-haptic feedback. These two different recall conditions were introduced to investigate if the recall mode interacts with the mode in which the movement is demonstrated (as in Feygin et al. 2002). With visual demonstration, participants only watched the movement on the screen. Thus they had to translate the information from the visual modality into the proprioceptive modality (Grindlay 2008) during recall.

This should be less difficult when vision is present during recall as well, so that the participants can reproduce the visual pattern on the screen. In contrast, under haptic-only recall, participants cannot resort to the visual information, and the translation of the visual modality into proprioception should be more error-prone. Therefore performance of the visually trained group should be superior when vision is added during recall. In contrast, the effects of added vision during recall when the movement was demonstrated haptically are more uncertain. Added vision might interfere with the haptic representation of the movement and might therefore decrease performance (as in Feygin et al. 2002). Alternatively, it might provide supplementary information about the movement that could be used in addition to the well-learned haptic information and therefore increase performance.

Methods

Participants

A total of 60 participants (42 female, 18 male; 19-33 years) volunteered for the study. Twenty of them participated in the visual group (13 female, 7 male; mean age: 25.5 years, SD: 3.3), 20 in the haptic group (17 female, 3 male; mean age: 24.2 years, SD: 2.7), and 20 in the visuo-haptic group (12 female, 8 male; mean age: 24.5 years, SD: 2.6). All participants were right-handed and had normal or corrected to normal vision according to their own declaration. They read and signed an informed consent form before the experiment that was done in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

Apparatus

The apparatus is shown in Figure 1. It consisted of a PC with a monitor (Iiyama S902JT VisionMaster Pro 451), a digitizer (Wacom Intuos4), and a robotic device

(Phantom Premium 1.5 A, SensAble Technologies). The connecting link at the end of the robot arm carried a hole into which the tip of the digitizer pen was inserted. The pen was held there by a minute rubber ring inside the walls of the hole, so that it could be tilted freely in all directions. Only with respect to horizontal movements the link between robot arm and tip of the pen was rigid. Participants drew with this pen on the digitizer. The position of the tip of the pen was mapped on the position of a cursor on the monitor, a green marker of five mm diameter. Position data were sampled at 100 Hz. To avoid injuries in case the Phantom should get out of control, a safety barrier was placed between it and the participant.

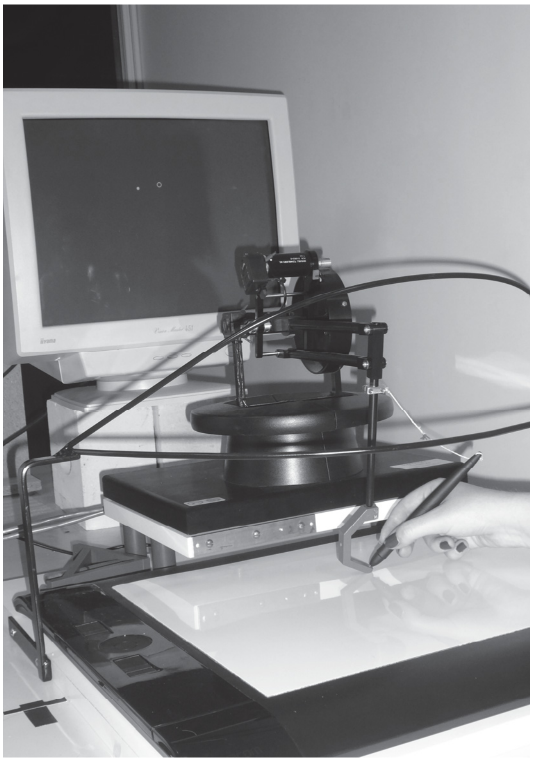

Fig. 1 Apparatus: Participants were seated in front of a digitizer tablet and faced a monitor. The tip of the pen was attached to the lower end of the stylus of a Phantom 1.5.

Design and procedure

The task of the participants was to learn a target movement with a certain velocity profile and to reproduce it afterwards. Based on the movements used in a study of

Shea, Lai, Wright, Immink, and Black (2001), we generated the target movement by defining the x- and y- coordinates of the start-, end-, and five reversal points. These were concatenated by segments of sine functions. Thus the target trajectory consisted of six sub-movements, lasting from one reversal point to the next. The sequence of (x, y) coordinates was transformed into position-time curves x(t) and y(t) for a total duration of 5 s. Finally the (discrete) time axis was nonlinearly transformed by

$$t(i) = t(i-1) + \Delta t * [1+0.5*\cos(2*\pi*i/n)]$$

with i=1…n, n as the total number of samples (500) and Δt = 10 ms. The transformation served to produce a velocity profile which started with a high acceleration and appeared rather inharmonious. The resulting movement path (a) and velocity profiles (b) are shown in Figure 2.

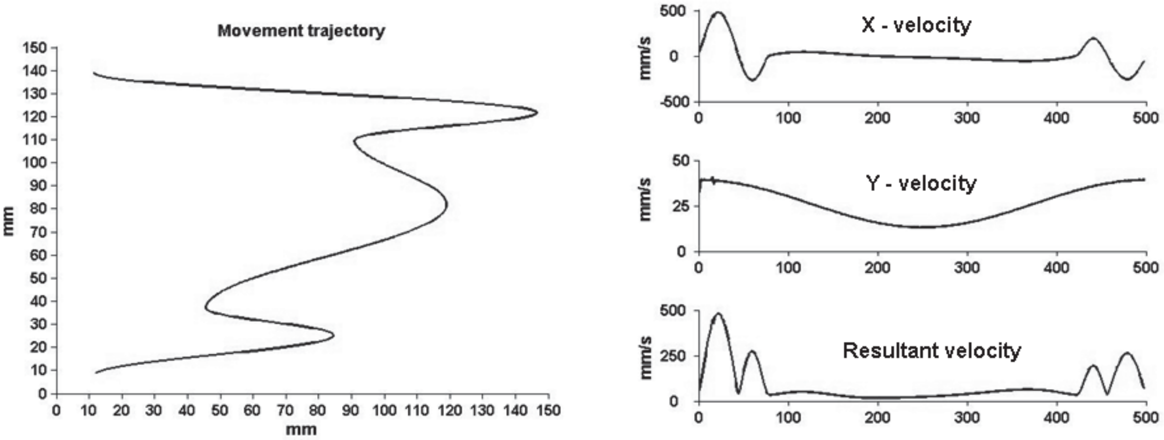

Fig. 2 Trajectory (a) and velocities (b) of the target movement.

Participants were randomly assigned to three different groups that differed in the way the movement was demonstrated to them, namely visually, hapticly, and visuo-hapticly. They were seated in front of the digitizer in a quiet and dimly lit room. They were instructed to watch the screen and wore earphones via which tones were presented and which shielded them from distracting auditory stimuli such as the drawing noise. After the instructions had been read, a familiarization trial was performed. During this familiarization trial the movement was demonstrated to the participant in the appropriate mode four times and should be reproduced afterwards four times. During two of these four reproductions the cursor was visible and during two reproductions participants performed without any visual feedback. Feedback conditions alternated.

All participants performed 12 trials with 30-s rest periods between them. The whole experiment took about one hour. Each trial consisted of a demonstration phase, in which the movement was demonstrated to the participants ten times, and a recall phase, in which participants reproduced the movement ten times as accurately as possible. To start each movement, during demonstration as well as during recall, participants moved the cursor to a start position on the screen, marked by a white outlined circle of 5 mm diameter. Two seconds after the start position had been reached, the movement began. Start and end of each movement were indicated by a tone.

The movements were demonstrated to each participant in one of three demonstration modes, depending on the group the participant was assigned to. In the visual group, participants watched the green filled circle which moved on the target trajectory with the appropriate velocity profile. They did not move their hand and were instructed to memorize the exact movement. In contrast, participants in the haptic group did not see the movement on the screen. As soon as they heard the tone and the movement began, the cursor disappeared. Instead, the movement was demonstrated to the participants hapticly by the Phantom device, which guided them while they faced the monitor. More specifically, there was a force field that drove the tip of the pen to the correct target position at each point in time. The force was $0.3d$ N, with d as the distance in mm of the current position of the tip of the pen from its current target position (upper limit: 10 N). Participants were instructed to let their hand be guided by the robot and to memorize the movement. The visuo-haptic group experienced a combination of the demonstration modes in the visual and haptic groups: participants were guided by the Phantom and saw the cursor moving on the screen simultaneously.

The task during the recall phase was the same for all participants: they were requested to reproduce the movement as accurately as possible ten times. For each reproduction they moved the cursor to the start position. After two seconds the tone was presented and participants should start their reproduction immediately. When the cursor did not move more than 0.2 mm for 500 ms, the end of the movement was detected and a tone was presented. To ensure that the movement was not terminated when the participant started it with a delay, the criterion for the end of the movement was applied not until two seconds after the start tone. During half of the reproductions, participants received visual feedback (visuo-haptic recall), i.e., they saw their movements on the screen, indicated by a green filled marker. In the other half of the reproductions there was no visual feedback (haptic recall). Participants were aware that feedback conditions alternated.

Data analysis

Only the reproductions were analyzed. First the position-time curves were low-pass filtered (fourth-order Butterworth, 5 Hz, dual-pass) and the velocities for the target and the cursor movement along both dimensions of the plane as well as the resultant velocity were computed (central-difference algorithm). Subsequently, start and end of the target and the cursor movement were determined. The start of each movement was defined as the first point where the resultant velocity exceeded 8 mm/s for at least 5 consecutive samples. The end of the movement was defined as the point where the resultant velocity exceeded 8 mm/s for the last time, followed by at least 5 consecutive samples with resultant velocity less than 8 mm/s.

The reversal points of each movement were determined by identifying those x-positions which exceeded the previous and the following one (in case of maxima) or where smaller than the previous and the following one (in case of minima). Sub-movements were defined to last from one reversal to the next one, with start- and end-positions serving as the first and the last reversal point. Movements with more or less than seven reversals were excluded from further analysis. In total 2.5 % of all reproductions with haptic feedback were excluded (visual group: 1.2 %, haptic group: 4.1 %, visuo-haptic group: 2.2 %). Among the reproductions with visuo-haptic feedback, 2 % of all movements were excluded (visual group: 1.0 %, haptic group: 2.4 %, visuo-haptic group: 2.6 %).

For each movement the durations and the amplitudes in the horizontal direction were computed for all sub-movements. The sums defined total duration and total amplitude. For each movement, *total-duration error* was determined as E, a measure of accuracy that includes both the response bias (constant error) and the variability (variable error) (see Shea et al. 2001). E was calculated as $E = \sqrt{(CE^2 + VE^2)}$, with CE as the constant error (mean total durations minus target durations) and VE as the variable error (standard deviation of total durations minus target durations).

To assess the accuracy of the profile of the durations of the sub-movements we adopted a procedure used by Heuer (1984). We treated the durations of the six sub-movements of each movement as a six-dimensional vector and computed the angle between this vector and the corresponding vector of the target movement. This angle, the *duration-profile error*, is zero when the vectors have the same direction, i.e., when the participant’s movement has the same duration profile as the target movement. The advantage of this measure is that it is insensitive to errors of total duration.

The analysis of spatial accuracy was performed in the same way as the analysis of temporal accuracy. Instead of using the durations of the six sub-movements, we used the horizontal amplitudes for computing the *total-amplitude error* and the *amplitude-profile error*. Thus we had two measures of temporal accuracy and two measures of spatial accuracy, each time one for the total error and one for the profile error.

Finally, we determined the accuracy of the resultant-velocity profile in terms of the correlation between the resultant velocity of the participant’s movement and the target resultant velocity (before computation of the correlations the reproductions had been normalized to the duration of the target movement, and the velocities had been recalculated from the normalized position-time curves). Besides the total-duration error and the duration-profile error, the *velocity-profile accuracy* served as an additional measure of dynamic accuracy.

Data for the 10 reproductions of each trial were averaged separately for the reproductions with and without visual feedback. The individual means (except for the first trial, where seven participants did not produce enough reproductions with the correct number of reversals) were entered in the statistical analyses. Two-way ANOVAs were run with demonstration condition (visual vs. haptic vs. visual+haptic) as between-participant factor and trial and recall condition (visuo-haptic feedback vs. haptic feedback) as within-participant factors. Greenhouse-Geisser corrections were applied when appropriate, but the uncorrected degrees of freedom are reported together with the Greenhouse-Geisser epsilon. Effect sizes are given as partial eta-squared.

Results

Dynamic accuracy

Total-duration error. The mean total-duration errors are presented in Figure 3 a. The three groups did not differ significantly, $F(2, 57) = 1.62$, $p = .21$, $\eta_p^2 = .05$, even though the total-duration error was numerically largest after visual demonstrations. There was no difference between the two recall conditions, $F(1, 57) = .63$, $p = .43$, $\eta_p^2 = .01$, and performance did not change across trials, $F(10, 570) = .95$, $p = .44$, $\varepsilon = .43$, $\eta_p^2 = .02$. When performance during only the last trial was analyzed, a significant difference between the three demonstration conditions emerged, $F(2, 57) = 4.06$, $p = .02$, $\eta_p^2 = .13$. A Bonferroni post-hoc-test revealed that only the haptic and the visual groups differed significantly ($p = .02$), whereas there was no difference between these groups and the visuo-haptic group.

Duration-profile error. Regarding the duration-profile error (Figure 3 b), the participants improved across trials, $F(10, 570) = 13.01$, $p < .01$, $\varepsilon = .65$, $\eta_p^2 = .19$, i.e., the profiles of the sub-movement durations became more similar to the target profile. The performance of the participants in the visuo-haptic recall condition was superior to the performance under the haptic recall condition, resulting in a significant main effect of the factor recall condition, $F(1, 57) = 16.78$, $p < .01$, $\eta_p^2 = .23$. Regarding the three demonstration conditions, the visuo-haptic group showed somewhat superior performance in the early stage of learning. In the first trial this difference was marginally significant, $F(2, 57) = 2.83$, $p = .07$, $\eta_p^2 = .09$. However, overall the difference between groups was not significant, $F(2, 57) = 1.14$, $p = .33$, $\eta_p^2 = .04$. None of the interactions was statistically significant.

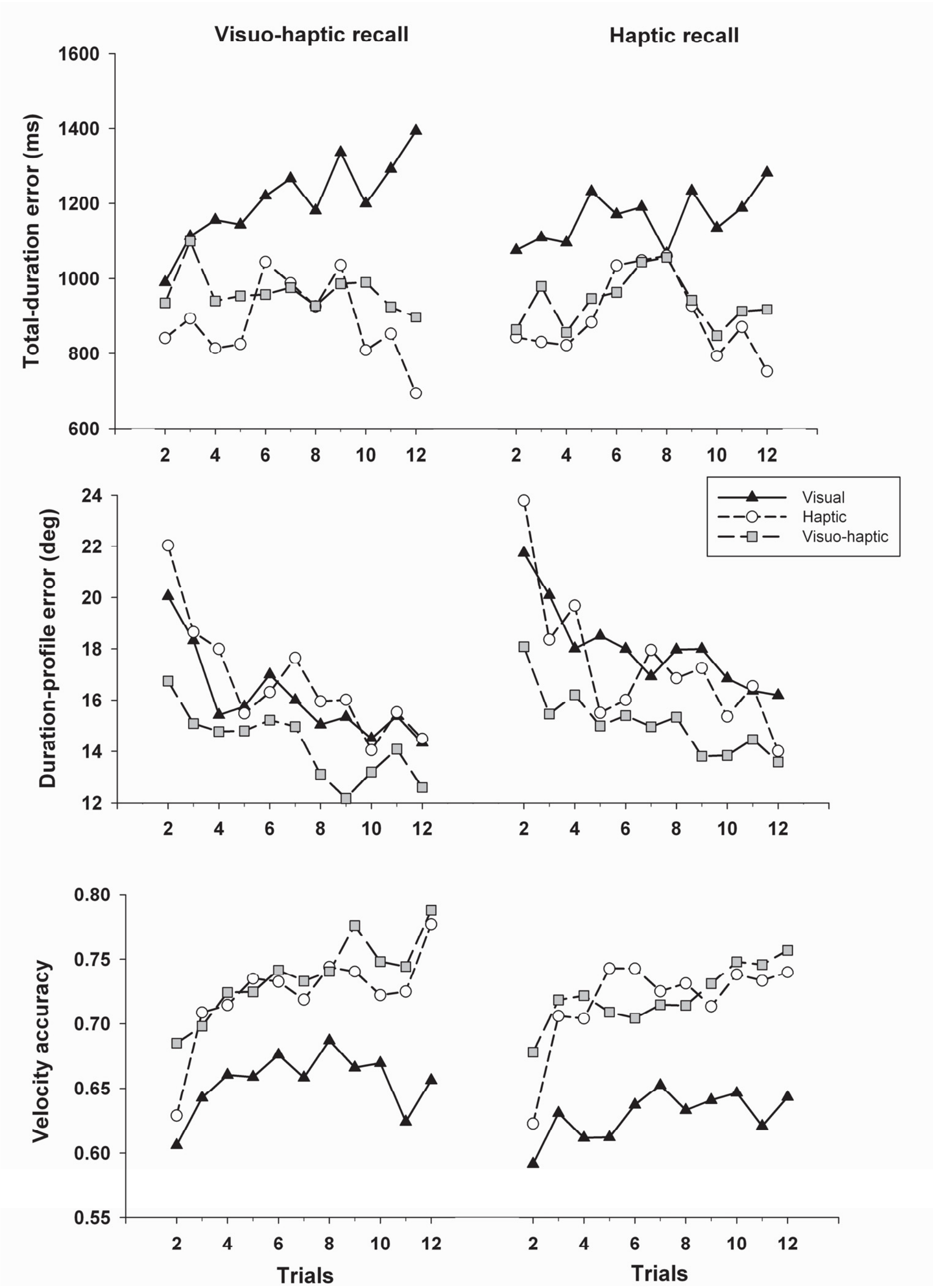

Fig. 3 Total-duration error (a), duration-profile error (b) and velocity accuracy (c) for the visual (black triangle), the haptic (white circle) and the visuo-haptic (grey square) group during visuo-haptic (left) and haptic (right) recall.

Velocity-profile accuracy. The mean correlations between the velocity profiles of the reproductions and the target movement are presented in Figure 3 c. The groups differed significantly in that the participants of the visual group had smaller correlations than the participants of the haptic and the visuo-haptic groups, $F(2, 57) = 3.90$, $p =$

.03, η_p^2 = .12. Furthermore, the improvement across trials was significant, $F(10, 570) = 7.07$, $p < .01$, $\varepsilon = .57$, $\eta_p^2 = .11$, and so was the somewhat better performance in the visuo-haptic than in the haptic recall condition, $F(1, 57) = 10.81$, $p < .01$, $\eta_p^2 = .16$. None of the interactions reached statistical significance.

A more detailed examination of the mean durations of the sub-movements and the averaged resultant-velocity profiles helps to understand the different findings for the duration-profile error and the velocity-profile accuracy. As can be seen in Figure 4 a, the differences between the three groups regarding the deviations from the target durations varied across the six sub-movements.

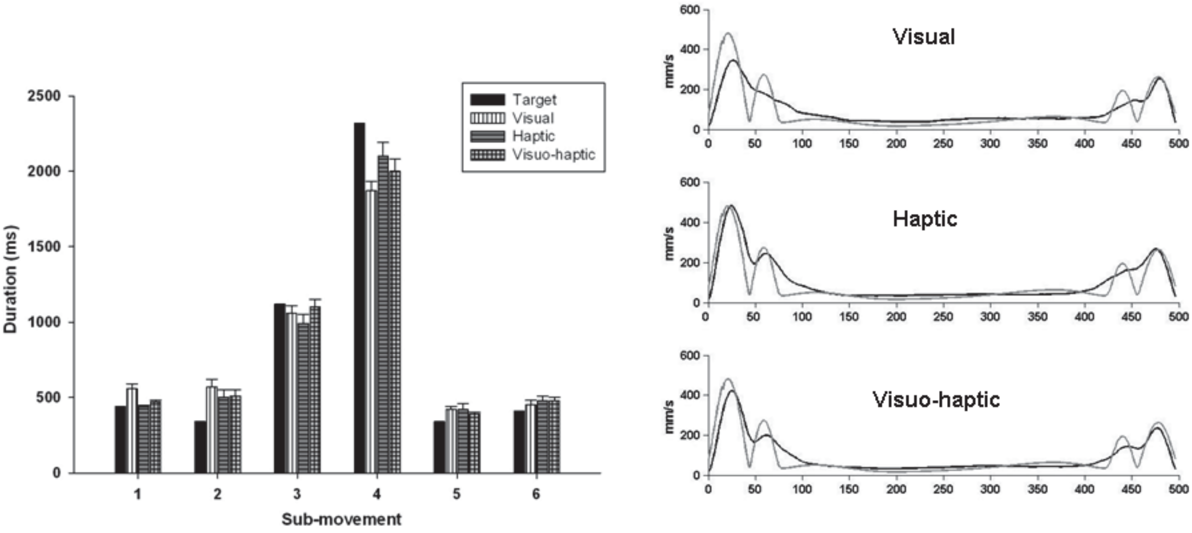

Fig. 4 (a): durations of the six movement-intervals for the target movement (black) and the average movements of the visual (white), the haptic (dark grey) and the visuo-haptic (light grey) group during the last trial. (b): Target resultant velocity (grey line) and average resultant velocity (black line) for the visual (top), the haptic (center) and the visuo-haptic (bottom) group during the last trial.

In particular during the first two as well as during the fourth sub-movement participants with haptic demonstrations were more accurate than participants with visual demonstrations. In determining the angle between the vectors with the observed sub-movement durations and the target durations each sub-movement has the same weight. In contrast, the correlation between the resultant velocities is strongly influenced by the large peaks at the beginning and the end of the movement. As can be seen in Figure 4 b, after visual demonstration the velocity modulation at the start of the movements deviated more from the target profile than the velocity modulation after haptic and visuo-haptic demonstration. Thus, the measures differ in their weighting of dynamic accuracy in different segments of the movements.

Spatial accuracy

Total-amplitude error. The mean total-amplitude errors are shown in Figure 5 a. Performance differed significantly between groups, $F(2, 57) = 3.54$, $p = .04$, $\eta_p^2 = .11$. A Bonferroni post-hoc-test revealed that only the visual and the haptic conditions differed significantly ($p = .03$). Errors were smaller in the visuo-haptic than in the haptic recall condition, $F(1, 57) = 22.26$, $p < .01$, $\eta_p^2 = .28$, and the interaction between recall condition and demonstration condition was significant, $F(1, 57) = 3.94$, $p < .02$, $\eta_p^2 = .12$. Whereas performance of the visual group was clearly superior to the performance of the visuo-haptic group in the visuo-haptic recall condition, in the haptic recall condition the performance became similar to that of the visuo-haptic group. All participants improved across trials, $F(10, 570) = 7.09$, $p < .01$, $\varepsilon = .45$, $\eta_p^2 = .11$. The recall condition x trial interaction was marginally significant, $F(10, 570) = 2.01$, $p = .054$, $\varepsilon = .68$, $\eta_p^2 = .03$.

Amplitude-profile error. Regarding the amplitude-profile errors (Figure 5 b), the ANOVA revealed a significant main effect of the demonstration condition, $F(2, 57) = 5.24$, $p < .01$, $\eta_p^2 = .15$. A Bonferroni post-hoc-test showed that only the performances of the visual and the haptic groups differed significantly ($p < .01$). After visual demonstration the amplitude-profile errors were smaller than after haptic demonstration. Furthermore errors declined across trials, $F(10, 570) = 17.22$, $p < .01$, $\varepsilon = .44$, $\eta_p^2 = .28$.

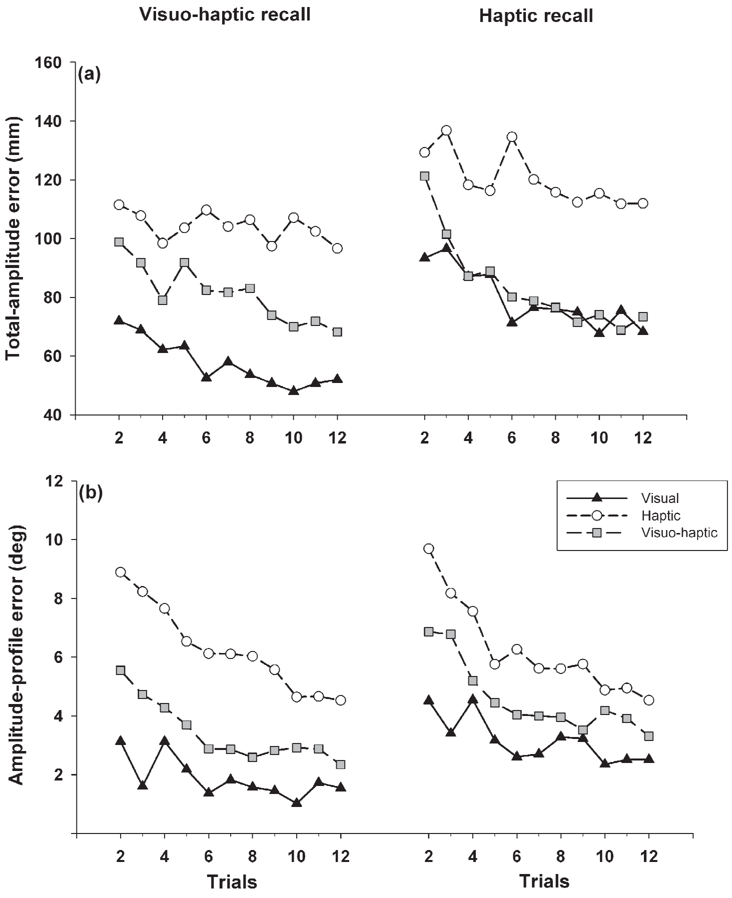

Fig. 5 Total-amplitude error (a) and amplitude-profile error (b) for the visual (black triangle), the haptic (white circle) and the visuo-haptic (grey square) group during visuo-haptic (left) and haptic (right) recall.

The interaction with demonstration condition just failed to reach statistical significance, $F(10, 570) = 1.71$, $p = .09$, $\eta_p^2 = .06$. Finally, participants performed better in the visuo-haptic than in the haptic recall condition, $F(1, 57) = 22.42$, $p < .01$, $\eta_p^2 = .28$. Also the interaction between recall and demonstration condition reached statistical significance, $F(1, 57) = 5.88$, $p < .01$, $\eta_p^2 = .17$. Basically the visual demonstration had stronger advantages as compared with haptic demonstration when visual feedback was available during recall than without visual feedback.

Discussion

In this experiment we compared the effects of different demonstration modes on the reproduction of a spatio-temporal motor pattern. Similar to the study of Feygin et al. (2002), the movement was demonstrated visually, hapticly or visuo-hapticly. It was reproduced in two alternating recall conditions, haptic and visuo-haptic. We will first discuss the differences between the visual and haptic demonstration groups regarding spatial and dynamic accuracy and thereafter move on to the performance of the combined visuo-haptic demonstration group.

Visual demonstration resulted in superior total-amplitude accuracy as compared with haptic demonstration. In addition the amplitude-profiles were more accurate in the visual than in the haptic group, i.e., the relative amplitude pattern was more similar to the target pattern when the movement was demonstrated visually. All groups showed learning; their errors declined in the course of practice, but the difference between the three demonstration conditions was present from the very start and changed little across trials.

Concerning total-duration error, there was only a tendency that haptic demonstration resulted in better performance than visual demonstration at the end of practice. Thus hapticly trained participants became more accurate in keeping the overall duration of five seconds. Performance did not change significantly across trials. For the duration-profile error, participants improved in the course of practice, but there was no difference between the three groups. Finally, the correlation between the velocity profiles of the reproductions and the target movement was significantly higher for the haptic than for the visual group. This difference mainly arose from the differences in the early part of the movements (see Figure 4). The target movement started with a strong acceleration, which was learned more accurately with the haptic than with the visual demonstration mode. The correlations increased throughout training which indicates learning.

The combined visual and haptic demonstration did not provide any significant further benefit for the spatial and temporal learning. The accuracy of the reproductions of this group was generally in-between the performance levels of the visual and the haptic group or similar to the superior group. The absence of a general improvement by combining visual and haptic demonstration is in accordance with the results of Feygin et al. (2002) and Liu et al. (2006). These authors argue that additional haptic training does not provide further benefit for the learning of spatial features since vision is more accurate for spatial characteristics. The same might be true for proprioception, which seems to be more accurate for dynamic movement features. Thus, combined training does not provide significant further benefit. The finding that the very small benefit of a combined demonstration in comparison to a haptic only training, if any, is present at a very early stage of learning corresponds in general to the finding by Grindlay (2008), who combined haptic and auditory training. However, the reasons for this slight and perhaps unreliable advantage are not clear.

Except for the learning of the total duration of the movement, added visual information during recall improved the learning of dynamic and spatial characteristics in all three groups. The interactions between recall and demonstration condition regarding the spatial aspects suggest that the visual group profited most from added visual feedback during recall. This is in accordance with our assumption that vision during recall particularly helps the visually trained participants in that they can reproduce the visual pattern on the screen. But different from the study of Feygin et al. (2002), also hapticly trained participants benefited from added vision during recall as well. This indicates that visual feedback can provide further information about both, time and space, independent of the way the movement was demonstrated to the participants.

Altogether, the results confirm the hypothesis that visual demonstration is superior for the learning of spatial movement characteristics, whereas haptic demonstration is beneficial for the learning of dynamic movement characteristics. These findings are consistent with those of previous studies on motor learning (e.g. Feygin et al. 2002; Grindlay 2008; Reinkensmeyer et al. 2007) and with observations on the perception and memory of visual, auditory, and haptic information. For example, Mahar, MacKenzie, and McNicol (1994) concluded that the senses of hearing and touch differ from vision with respect to the specialization for the processing of temporally versus spatially ordered patterns. Regarding motor learning in more general terms, different effects of different training methods should be related to distinct processes of motor control and their neural substrates. From this perspective the present findings are in line with the notion of separate control of spatial and temporal movement characteristics, perhaps involving different neural substrates (cf. Georgopoulos 2002).

Finally two possible caveats against our conclusion should be mentioned. First, the visual and haptic demonstration differed with respect to the plane of motion. In the haptic condition the movement was demonstrated in the horizontal plane, whereas in the visual condition the movement was demonstrated on the screen, thus in the vertical plane. All reproductions were performed in the horizontal plane. However, it seems highly unlikely that the use of different planes of demonstration and reproduction should have facilitated the learning of spatial characteristics, but the use of the same plane the learning of temporal characteristics. Second, in this experiment as well as in most of the previous studies (e.g. Feygin et al. 2002; Liu et al. 2006; Grindlay et al. 2008) only short-term learning was investigated. Thus an important question for further studies is if the different effects of visual and haptic demonstration on spatial and dynamic performance can still be found after a longer delay, for example overnight.

As a broad implication for movement training, we can maintain that robotic guidance is beneficial for learning those characteristics of a movement that are hard to demonstrate visually, and these are dynamic characteristics in particular. This is true in the short run, and it may also be true in the long run, though this is not yet established. Different from previous observations, the results further suggest that adding vision during recall might always lead to further performance improvement, independent of the demonstration modality.

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References

Armstrong TR (1970) Feedback and perceptual-motor skill learning: A review of information feedback and manual guidance training techniques. Tech Rep No 25, Ann Arbor, University of Michigan, Department of Psychology

Bluteau J, Coquillart s, Payan Y, Gentaz E (2008) Haptic guidance improves the visuo-manual tracking of trajectories. Plos One 3: e1775

Feygin D, Keehner M, Tendick F (2002) Haptic guidance: Experimental evaluation of haptic training method for a perceptual motor skill. P 10th Int Symposium Haptic Interfaces Virtual Environ Teleoperator Syst (Haptics 2002): 40-47

Georgopoulos AP (2002) Cognitive motor control: spatial and temporal aspects. Curr Opin Neurobiol 12: 678-683.

Grindlay G (2008) Haptic guidance benefits musical motor learning. P Symposium Haptic Interfaces Virtual Environ and Teleoperator Syst: 397-404

Gillespie RB, O'Modhrain MS, Zaretzky D, Pham C (1998) The virtual teacher. ASME Int Mech Eng Conf Expo

Henmi K, Yoshikawa T (1998) Virtual lesson and its application to virtual calligraphy system. P 1998 IEEE Int Conf Robotics Automation 2: 1275-1280

Heuer, H (1984) On re-scalability of force and time in aiming movements. *Psychol Res 46:* 73-86

Holding DH (1970) Learning without errors. In Smith LE (ed.) Psychology of motor learning. Athletic Institute, Chicago, pp 59-74

Holding DH, Macrae, AW (1964) Guidance, restriction and knowledge of results. *Ergonomics 7:* 289-295

Krauth J (1995) Testkonstruktion und Testtheorie. Psychologie Verlags Union, Weinheim

Liu J, Cramer SC, Reinkensmeyer DJ (2006) Learning to perform a new movement with robotic assistance: comparison of haptic guidance and visual demonstration. J NeuroEng Rehabil 3

Lüttgen J, Heuer H (in press) The influence of haptic guidance on the production of spatio-temporal patterns. Hum Movement Sci. doi:10.1016/j.humov.2011.07.002

Mahar D, MacKenzie B, McNicol D (1994) Modality-specific differences in the processing of spatially, temporally, and spatiotemporally distributed information. Percept 23: 1369-1386

Marchal-Crespo L, Furumasu J, Reinkensmeyer DJ (2010) A robotic wheelchair trainer: design overview and a feasibility study. J NeuroEng Rehabil 7

Marchal-Crespo L, Reinkensmeyer DJ (2008a) Haptic guidance can improve motor learning of a steering task. J Motor Behav 40: 545-556

Marchal-Crespo L, Reinkensmeyer DJ (2008b) Effect of robotic guidance on motor learning of a timing task. P 2nd Biennial IEEE/RAS-EMBS Int Conf Biomed Robotics and Biomechatron: 199-204

Marchal-Crespo L, Reinkensmeyer DJ (2009) Review of control strategies for robotic movement training after neurologic injury. J NeuroEng Rehabil 6

Milot M-H, Marchal-Crespo L, Green CS, Cramer SC, Reinkensmeyer DJ (2010) Comparison of error-amplification and haptic guidance training techniques for learning of a timing-based motor task by healthy individuals. Exp Brain Res 201: 119-131

Palluel-Germain R, Bara F, Hillairet de Boisferon A, Hennion B, Gouagout P, Gentaz E (2006) Early handwriting acquisition: Evaluation of Telemaque, a new visuo-haptic interface. P euroHaptics: 551-554

Palluel-Germain R, Bara F, Hillairet de Boisferon A, Hennion B, Gouagout P, Gentaz E (2007) A visuo-haptic device – Telemaque – increases kindergarten children's handwriting acquisition. P IEEE World Haptics 2007: 72-77

Poulton EC, Freeman PR (1966) Unwanted asymmetrical transfer effects with balanced experimental designs. Psychol Bull 66: 1-8

Reinkensmeyer DJ, Emken JK, Cramer SC (2004) Robotics, motor learning, and neurological recovery. Annu Rev Biomed Eng 6: 497-525

Reinkensmeyer DJ, Galvez JA, Marchal-Crespo L, Wolbrecht ET, Bobrow JE. (2007) Some key problems for robot-assisted movement therapy research: a perspective from the University of California at Irvine. P 2007 IEEE Int Conf Rehabil Robotics: 1009 -1025

Reinkensmeyer DJ, Patton, JL (2009) Can robots help the learning of skilled actions? Exercise Sport Sci R 37: 43-51

Schmidt RA, Lee TD (1999) Motor control and learning-a behavioral emphasis, 3rd edn. Human Kinetics, Champaign, IL, pp 316-317

Shea CH, Lai Q, Wright DL, Immink M, Black C (2001) Consistent and variable practice conditions: effects on relative and absolute timing. J Motor Behav 33: 139-152

Solis J, Avizzano CA, Bergamasco M (2002) Teaching to write japanese characters using a haptic interface. P 10th Int Symposium Haptic Interfaces Virtual Environ Teleoperator Syst (Haptics 2002): 255-262

Teo C, Burdet E, Lim H (2002) A robotic teacher of Chinese handwriting. P 10th Int Symposium Haptic Interfaces Virtual Environ Teleoperator Syst: 335-341