Aus dem Lehrstuhl für Bewegungswissenschaft

der Technischen Universität München

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Antizipative Anpassung von Griffkräften während des Hebens von Alltagsgegenständen bei Gesunden und nach unilateraler Hirnschädigung

Dissertation

zum Erwerb des Doktorgrades der Medizin

an der Medizinischen Fakultät der

Ludwig-Maximilians-Universität zu München

vorgelegt von

Sandra Hörmann, geb. Eidenmüller

aus

Dachau

2019

Mit Genehmigung der Medizinischen Fakultät

der Universität München

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Tag der mündlichen Prüfung: 11.04.2019

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Weilheim, 11. September 2019	Sandra Hörmann
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Inhaltsverzeichnis

Abkürzungsverzeichnis

CL	Kontrollgruppe links
CR	Kontrollgruppe rechts
dPM	Dorsale prämotorischer Kortex
fMRT	funktionelle Magnetresonanztomografie
GFR	Griffkraftrate/grip force rate
LBD	left brain damage
LFR	Lastkraftrate
M1	Primär motorische Kortex
RBD	right brain damage
S1	Somatosensorischer Kortex
SMA	Supplementär-motorische Kortex
TMS	transkranielle Magnetstimulation

Publikationsliste

Veröffentlichung I:

Eidenmuller, S., Randerath, J., Goldenberg, G., Li, Y., & Hermsdorfer, J. (2014). The impact of unilateral brain damage on anticipatory grip force scaling when lifting everyday objects. *Neuropsychologia, 61*, 222-234.

Veröffentlichung II:

Hermsdörfer, J., Li, Y., Randerath, J., Goldenberg, G., Eidenmüller, S. (2011). Anticipatory scaling of grip forces when lifting objects of everyday life. *Exp. Brain Res., 212*, 19-31.

Vorstellung im Rahmen einer Postersession:

55. Jahrestagung der Deutschen Gesellschaft Klinische Neurophysiologie und funktionelle Bildgebung (DGKN, 16-19.03.2011)

Postertitel:

The impact of unilateral brain damage on anticipatory force scaling when lifting everyday life objects. *S.Eidenmüller, J. Randerath, G.Goldenberg, Y. Li, J. Hermsdörfer*

Einleitung

der schriftlichen, kumulativen Promotion

gemäß § 4a der Promotionsordnung der LMU vom 1. Juni 1983 in der zehnten Fassung der Änderungssatzung vom 6. Juli 2012

Zielsetzung der Untersuchung

Täglich greifen wir nach hunderten von Objekten und benutzen diese geschickt und automatisiert, unser Alltag ist von Objektgebrauch dominiert. Aufstehen, Zähne putzen, Frühstück bereiten. Bereits kurz nach dem Erwachen haben wir eine Vielzahl von Handlungen völlig automatisch ausgeführt. Um Objekte im Alltag richtig einschätzen zu können, haben Gesunde die Fähigkeit die Kraft, mit der sie zugreifen, passend dem Objektgewicht zu skalieren. Ein „Herantasten“ ist bei bekannten Objekten nicht notwendig. Die Wahrnehmung von Objekteigenschaften wie Größe oder Material, sowie Vorerfahrung mit den zu handhabenden Objekten spielen eine wichtige Rolle bei der Vorausplanung von Bewegungen (Cole, 2008; Flanagan, King, Wolpert & Johansson, 2001; Gordon, Forssberg, Johansson & Westling, 1991a, 1991b; Johansson & Westling, 1988; Li, Randerath, Goldenberg & Hermsdörfer, 2007; Witney, Vetter & Wolpert, 2001). Dies geschieht bei Gesunden wie von selbst und nebenbei, ohne dass dies besonderer Aufmerksamkeit oder Konzentration bedarf. Doch worauf basiert diese Fähigkeit, wie wird sie durch Hirnschädigung beeinflusst und welche Rolle spielt dabei die Funktionsstörung Apraxie?

Um im Allgemeinen Aussagen bezüglich antizipativer Fähigkeiten während der Objektmanipulation treffen zu können, haben sich Analysen der Greif-Kinetik etabliert. Dazu werden, wie auch in der vorliegenden Studie, Sensoren an den Fingern befestigt, die die Griffkraft messen. Da die Kraft, mit der die Objekte gegriffen werden, vorausgeplant wird und bereits im Moment des Zugreifens an das Objekt angepasst ist, ist vor allem die sogenannte „Loading-Phase“, also die Zeit vom Greifen bis zum Abheben der Objekte von besonderem Interesse.

Die vorliegende Arbeit macht es sich zum Ziel, die Fähigkeit der antizipativen Griffkraftskalierung im Alltag nachzuweisen und in einem zweiten Schritt zu sehen, inwieweit unilaterale Hirnschädigung nach Schlaganfall diese Fähigkeit beeinflusst. Dazu hoben Gesunde und Patienten eine große Auswahl an Alltagsgegenständen (zum Beispiel einen Zahnputzbecher, eine Packung Kekse oder ein Buch) mit einer hohen

Varianz der Objektgewichte, dabei wurde neben anderen Parametern die Griffkraft ermittelt.

In der ersten vorliegenden Studie hoben gesunde Probanden die Objekte unter zwei verschiedenen Bedingungen. Unter der ersten Bedingung war die Objektidentität durch einheitliches Papier verborgen, unter der zweiten Bedingung waren die Objekte nicht verhüllt und wurden so von den Probanden als Alltagsgegenstand erkannt. Wir interessierten uns dafür, ob das Identifizieren der Objekte im Vergleich zu der Bedingung, in dem die Objektidentität verborgen war, zu einer besseren initialen Griffkraftskalierung führt.

Im Mittelpunkt der zweiten Arbeit stehen Patienten nach unilateraler Hirnschädigung. Wir stellen die Hypothese auf, dass Patienten nach Schlaganfall der linken Hemisphäre unter eingeschränkter Griffkraftantizipation leiden, dies jedoch nicht unbedingt mit anderen Symptomen defizitärer Bewegungsplanung wie beispielsweise Apraxie korreliert. Dazu werden Daten von 26 Patienten des Klinikums Bogenhausen mit unilateraler Hirnschädigung nach Schlaganfall vorgestellt. Die Patienten hoben dieselben alltäglichen Objekte mit der ipsiläsionalen Hand wie in der erstgenannten Studie, jedoch nur unter der „unverhüllten“ Bedingung. Dabei wurde wiederum der Hebevorgang analysiert. Die Ergebnisse wurden mit Kontrollgruppen (passend zu den Patientengruppen hoben gesunde Rechtshänder in 2 Gruppen mit der linken oder rechten Hand die Objekte) verglichen und mit verschiedenen Apraxie- Tests korreliert. Mit Hilfe der Läsionsanalyse versuchten wir, die neuronalen Substrate, welche für Antizipation von Griffkraft im Alltag entscheidend sind, weiter einzugrenzen.

Die hohe Inzidenz des Schlaganfalls und der hohe Bedarf an neurologischer Rehabilitation im Bereich der Aktivitäten des alltäglichen Lebens liefern viele Gründe dafür, die Forschung im Bereich der Apoplexie voran zu treiben. Das Ziel der vorliegenden Arbeit ist es daher, einen Beitrag zur Grundlagenforschung im Bereich Griffkraftantizipation im Allgemeinen sowie nach unilateraler Hirnschädigung zu leisten.

Einleitung und Grundlagen

Antizipative Anpassung der Griffkraft bei abstrakten und alltäglichen Objekten

Essentiell für eine geschickte und geschmeidige Interaktion mit Objekten ist die Fähigkeit, deren physikalische Eigenschaften im Alltag vorhersagen zu können. Dies ermöglicht uns, das Wissen entsprechend in den motorischen Plan zu integrieren und das jeweilige Objekt mit passender Griffkraft zu greifen (antizipatives Greifen). Objektgebrauch im alltäglichen Leben wäre langsam und ungeschickt, wenn wir uns vor dem Greifen jedes Mal neu „herantasten" müssten, sprich, wenn wir auf sensorische Feedback-Informationen beim Bewegungsablauf angewiesen wären. Zudem ermöglicht uns antizipatives Greifen einen sicheren Umgang mit Objekten. Andernfalls würden fragile Objekte, wie etwa eine Himbeere, bei initial zu hoher Griffkraft beschädigt werden oder schwere Gegenständen würden bei zu niedrig kalkulierter Kraft aus der Hand gleiten.
Johansson und Westling konnten 1988 zeigen, dass die Stärke der Griffkraft bereits vor dem Abheben bestimmt und dabei an das Gewicht des Objektes angepasst wird. Zu diesem Zweck hoben Probanden Objekte unter zwei verschiedenen Bedingungen. Im ersten Durchgang änderte sich das Gewicht nicht, im zweiten Durchgang änderte sich das Gewicht, ohne dass die Probanden dies vorhersehen konnten. Die dabei abgeleiteten Parameter (Griffkraft und vertikale Lastkraft) zeigten an, dass die Griffkraft jeweils dem vorher gehobenen Objekt angepasst war. Folglich war der Hebevorgang unter der ersten Bedingung zu den Objekten passend und bedurfte keiner Modulation mehr. Entsprechend waren die Parameter unter der zweiten Bedingung initial nicht passend und mussten dem Objektgewicht im Laufe des Hebevorgangs angepasst werden. Die gewichtspezifische Griffkraftmodulation erfolgte antizipativ.
Die Kraft, die aufgebracht wird, um Dinge zu greifen oder zu benutzen, ist äußerst ökonomisch dosiert, das heißt es wird gerade so viel Kraft einsetzt wird, dass der Gegenstand nicht aus der Hand rutscht (Johansson & Westling, 1984).

Gesunde Erwachsene überschreiten die minimale Kraft, die notwendig ist, damit das Objekt nicht aus der Hand rutscht, um nur 20% und verringern diesen Sicherheitsabstand bei allen weiteren Hebevorgängen mit demselben Objekt (Johansson & Westling, 1987).

Als Beispiel für Fehleinschätzung des Gewichts lässt sich das Kofferbeispiel nennen. Erwarten wir einen gefüllten Koffer obwohl dieser leer ist, setzen wir die Kraft, mit der wir zupacken, zu hoch an und es kommt zum Hochreißen des Objekts.

Zusammenfassend lässt sich sagen, dass antizipative Objektmanipulation sowohl die Dynamik der Objekte, als auch die Dynamik des eigenen Körpers vorhersieht und den motorischen Plan entsprechend anpasst, ohne initial auf Informationen aus der sensorischen Rückkopplung angewiesen zu sein.

Analyse des Greifens im Hinblick auf antizipative Fähigkeiten

Bevor im Weiteren auf die Objekteigenschaften eingegangen wird, welche uns wertvolle Hinweise zur antizipativen Griffkraftskalierung geben, lohnt es sich, einen Blick darauf zu werfen, wie das Greifen und Heben eines Objektes strukturiert ist und anhand welcher Parameter sich Antizipation messen lässt. Das Greifen, Heben und wieder- Abstellen von Objekten lässt sich in verschiedene Phasen unterteilen. Steht die Fähigkeit zur Antizipation im Vordergrund, ist vor allem die Zeit vom Fingerkontakt bis zum Abheben des Objektes von besonderem Interesse, da hier noch keine Information aus sogenannten sensorischen Feedback- Mechanismen zur Verfügung steht. In dieser Phase des Hebevorgangs lassen sich die Lastkraft- und die Griffkraftrate ableiten. Die Lastkraft wird mit Hilfe einer Waage ermittelt und wirkt senkrecht zum Objekt. Sobald die Lastkraft die Gewichtskraft erreicht, hebt das Objekt ab. Die Griffkraft tritt orthogonal zur Kontaktfläche auf. Lastkraft- und Griffkraftrate beschreiben jeweils, wie schnell die Kraft entwickelt wird (Einheit jeweils N/s). Bei antizipativem Greifen zeigen sowohl Griffkraft- als auch Lastkraftrate einen eingipfligen Verlauf. Der eingipflige Verlauf lässt sich dadurch erklären, dass der Proband im Bewegungsplan eine bestimmte zu erreichende Kraft festgelegt hat und so zielstrebig diese Kraft entwickelt.

Mehrgipflige Verläufe sind bei Objekten mit unbekanntem Gewicht typisch, da sich hier der Proband „herantastet“ und eventuell die Kraft nochmal anpasst, da das Ziel nicht klar festgelegt ist. Hierbei ist zu betonen, dass die Höchstwerte von Lastkraft- und Griffkraftrate noch vor dem Abheben erreicht werden.
Studien, die das Greifen von Alltagsgegenständen mittels Kraftparametern untersuchen, waren bisher selten und auf das Messen der Lastkraft beschränkt, was jedoch gewisse Schwierigkeiten mit sich bringt. Zum einen ist die Lastkraft durch das Gewicht der Objekte beschränkt (maximal die Gewichtskraft des Objektes), während die Griffkraft fast uneingeschränkt hoch sein kann, solange das Objekt nicht beschädigt wird. Zum anderen gibt es Hinweise darauf, dass Griffkraft und Lastkraft unterschiedlicher neuronaler Repräsentation unterliegen (Rabe et al., 2009).
Aus zahlreichen Studien mit abstrakten Objekten weiß man, dass die maximale Griffkraftrate vor Abheben des Objekts (eingipfliger Verlauf) der sensitivste Parameter ist, um antizipatives Greifen und Heben von Objekten nachzuweisen (Flanagan & Beltzner, 2000; Gordon et al., 1991b; Johansson & Westling, 1988; Li et al., 2009; Nowak, Timmann & Hermsdörfer, 2007).
In den beiden vorliegenden Studien wurden Griffkraft und Lastkraft bestimmt und Korrelationen zwischen beiden Kraftraten und den jeweiligen Objektgewichten ermittelt.

Prädiktoren der Objektdynamik

Welche Objekteigenschaften geben uns nun die entscheidenden Hinweise, um die Griffkraft entsprechend an das Objekt anpassen zu können?
Als wichtigste Orientierungshilfe ist die Objektgröße zu nennen, sofern das Material bekannt ist. Es konnte in zahlreichen Studien gezeigt werden, dass das Objektgewicht anhand der Größe geschätzt und die zum Abheben nötige Kraft antizipiert wird (Cole, 2008; Flanagan & Beltzner, 2000; Gordon et al., 1991a; Li et al., 2009; Li, Randerath, Goldenberg & Hermsdörfer, 2011). Als weitere, wichtige Prädiktoren sind Form,

Oberflächenbeschaffenheit, sowie die Verteilung des Gewichts am Objekt zu nennen (Cadoret & Smith, 1996; Cole, 2008; Eidenmuller, Randerath, Goldenberg, Li & Hermsdorfer, 2014; Flanagan & Beltzner, 2000; Flanagan, Bittner & Johansson, 2008; Gordon, Westling, Cole & Johansson, 1993; Jenmalm & Johansson, 1997; Salimi, Hollender, Frazier & Gordon, 2000).

Ein weiterer wichtiger Prädiktor für das Gewicht und andere Objekteigenschaften sind Erfahrungen mit demselben Objekt aus aufeinander folgenden Hebevorgängen. In Studien, in denen zwei Objekte unterschiedlichen Gewichts aber selber Größe und Erscheinung gehoben wurden (und damit die Objekte selbst keinen verlässlichen Hinweis brachten), konnte nachgewiesen werden, dass sich die Probanden am Gewicht der vorher gehobenen Objekte orientierten (Flanagan et al., 2001). Zudem wissen wir, dass wir in der Lage sind, sehr schnell Assoziationen zwischen der Objektfarbe und dem Gewicht zu erlernen und folglich die Griffkraft passend zu antizipieren (Cole & Rotella, 2002). Dieses Wissen bleibt für mindestens 24h erhalten (Flanagan et al., 2001; Gordon et al., 1993; Nowak, Koupan & Hermsdorfer, 2007). Interessanterweise gelingt es uns nicht, eine Assoziation zwischen eigenem Handeln und der daraus resultierenden Änderung des Objektgewichts zu ziehen. Wenn aus einem vollen Glas Wasser die Hälfte mit Hilfe eines Strohhalms ausgetrunken wird, hat dies keine Reduktion der Griffkraft beim anschließenden Hochheben zur Folge. Offensichtlich ist direkter, haptischer Kontakt zum Objekt notwendig, um das sensomotorische Gedächtnis zu aktualisieren (Nowak & Hermsdorfer, 2003). Überraschend mögen auch die Ergebnisse sogenannter „size-weight-illusion“-Studien erscheinen. Hier ließ sich wiederholt nachweisen, dass das kleinere zweier gleich schwerer Objekte sich für Probanden auch nach mehreren Durchgängen schwerer als das Große anfühlt, jedoch die initiale Griffkraft nach einem Übungsdurchgang für beide Objekte ähnlich hoch angesetzt wird. Aus dem Widerspruch zwischen der Wahrnehmung des Gewichts (Gewicht wird als zu hoch beurteilt) und der jedoch passenden Griffkraft wird gefolgert, dass das sensomotorische und das perzeptive System unabhängig voneinander arbeiten (Flanagan & Beltzner, 2000; Flanagan et al., 2001).

Bisherige Studien zu antizipativer Griffkraftskalierung waren bis auf wenige Ausnahmen auf abstrakte Objekte reduziert. Es gibt eine Studie von Gordon (Gordon et al., 1993), welche das Greifen und Heben von Alltagsgegenständen wie von einem Videoband oder einer Tasse bei gesunden Probanden untersucht hat. Hier wurden die maximale Lastkraftrate und die Zeit zwischen dem ersten Fingerkontakt und dem Abheben des Objekts erhoben. Beide Messungen zeigten charakteristische Ergebnisse für jedes einzelne Objekt. Daraus lässt sich folgern, dass auch bei Alltagsgegenständen die physikalischen Eigenschaften bereits vor dem Abheben die Lastkraftentwicklung beeinflussen und folglich die Objekteigenschaften unabhängig von sensorischen Feedbackinformationen antizipiert werden. Zu ähnlichen Ergebnissen kam eine Studie, bei der gesunde Kinder und Kinder mit Zerebralparese Alltagsgegenstände hoben (Duff & Gordon, 2003), sowie eine Studie, die Daten von Patienten nach linkshemisphärischer Hirnschädigung erhoben hat (Dawson, Buxbaum & Duff, 2010). In der letztgenannten Studie zeigten zwei Patienten mit Apraxie keine klare Korrelation zwischen dem Objektgewicht und der Lastkraftentwicklung.

Zusammengefasst lässt sich aus den genannten Studien folgern, dass Objekte aus dem Alltag wiedererkannt werden. Dabei können wir aus dem assoziativen Gedächtnis Informationen bezüglich der Objekteigenschaften abrufen und so die Griffkraft vorausschauend skalieren.

Neuronale Korrelate antizipativer Griffkraftskalierung

Die bisherigen Studien, welche sich mit Griffkraftskalierung beschäftigen, untersuchten meist das Heben von abstrakten Objekten, wie Zylindern und Boxen verschiedener Größen. Dabei gibt vor allem die Größe den entscheidenden Hinweis, wie schwer das Objekt sein könnte. Nur vereinzelt gibt es Arbeiten, welche das Heben von Alltagsgegenständen untersuchten. Dies hat vor allem technische Gründe. Das Ausstatten von Alltagsobjekten mit Griffkraftsensoren ist praktisch schwierig umzusetzen. Jedoch spielt im Alltag die Objektgröße bezüglich der Griffkraftskalierung eine nur untergeordnete Rolle. Es gibt große Objekte, welche sehr leicht sind (z.B. aus Styropor) oder auch umgekehrt kleine Objekte, die überraschend schwer sind. Im

Alltag gibt uns also die Objektidentität, sofern wir den Gegenstand kennen und zuordnen können, den entscheidenden Hinweis, welche Griffkraft adäquat zum jeweiligen Objekt ist.

Doch wie erlernen wir mit Hilfe von Assoziationen zwischen Objekteigenschaften und Objektgewicht die Griffkraft passend zu skalieren? Was passiert auf neuronaler Ebene? Zunächst ist bekannt, dass wir bei unbekanntem Objektgewicht die Griffkraft passend zum unmittelbar zuvor gehobenen Objekt anpassen. Der zentrale Speicher, in dem die Informationen von einem Hebeversuch zum nächsten integriert werden, wird sensomotorisches Gedächtnis genannt. Um im Allgemeinen Hirnregionen zu erfassen, welche in das Kodieren und Speichern von Objektinformationen involviert sind, haben sich funktionale Magnetresonaztomografie- Studien (fMRT) und Studien mit transkranieller Magnetstimulation (TMS) bewährt. Beispielsweise zeigte sich bei einer fMRT-Studie während dem wiederholten Heben von Objekten mit unbekannten physikalischen Eigenschaften ein großes Netzwerk der sensomotorischen Hirnregionen aktiviert. Während Probanden die Objekte wiederholt mit der rechten Hand hoben, ließen sich Aktivitäten im primär somatosensorischen und motorischen Kortex links (S1/M1), im linken dorsalen prämotorischen Kortex (dPM), im linken Operculum, im supplementär motorischen Kortex (SMA), im Bereich der linken Fissur und in beiden Kleinhirnhemisphären nachweisen (Schmitz, Jenmalm, Ehrsson & Forssberg, 2005).

Um jedoch im Alltag geschickt mit Objekten umzugehen, ist es essentiell, dass diese kurzfristig erworbenen, somatosensorischen Gedächtnisinhalte langfristig mit charakteristischen Eigenschaften für das jeweilige Objekt verknüpft werden. Wir wissen, dass Assoziationen zwischen einer willkürlichen Objektfarbe oder auch einem akustischen Signal und dem Objektgewicht leicht zu erlernen sind (Ameli, Dafotakis, Fink & Nowak, 2008; Cole & Rotella, 2002). Mit Hilfe dieser visuellen oder akustischen Hinweise kann nun die Griffkraft passend zum Objekt antizipiert werden. Wir gehen davon aus, dass dies bei Alltagsobjekten ein ähnlicher Prozess ist. Trifft man wiederholt auf ein Objekt, ist es uns möglich, die interne Repräsentation des Objektes abzurufen und die sehr frühe Griffkraft entsprechend zu antizipieren (Ameli et al., 2008; Nowak et al., 2007).

Bisher gibt es keine Studie mit bildgebenden Verfahren während des Greifens und Hebens von Alltagsgegenständen. So ist uns über die neuronalen Substrate, welche uns Antizipation im Alltag ermöglichen, wenig bekannt. Es gibt eine fMRT-Studie, die untersucht hat, welche Hirnregionen während dem Knüpfen von neuen Assoziationen aktiv werden. Hierbei wurden Probanden aufgefordert jeweils ein leichtes und ein schweres Objekt gleicher Größe zu heben. Die Objekte waren farblich markiert, so dass die Probanden nach dem ersten Hebeversuch in der Lage waren, die Objekte zu unterscheiden und somit die Griffkraft zu antizipieren (van Nuenen, Kuhtz-Buschbeck, Schulz, Bloem & Siebner, 2012). Dabei zeigten sich beidseitige Aktivitäten des dorsalen prämotorischen Kortex (dPM), der medialen Anteile des prämotorischen Kortex, sowie des supplementär motorischen Kortex (SMA). Während des Hebes des schweren Objektes zeigten sich zusätzlich Aktivitäten im linken Partialhirn. Passend zu diesem Studienergebnis führte transkranielle Magnetstimulation im Bereich des dorsalen, prämotorischen Kortex zu eingeschränkter Griffkraftantizipation, wenn das Objektgewicht mit Hilfe neu erlernter Assoziationen antizipiert werden sollte (Chouinard, Leonard & Paus, 2005; Nowak et al., 2009; van Nuenen et al., 2012).
Aus weiteren fMRT-Studien lässt sich ableiten, dass verschiedene Objekteigenschaften auch von verschiedenen Hirnregionen berechnet werden. Die Größe wird in S1 links und in linken anterioren intraparietalen Bereichen (AIP) präsentiert. Das Gewicht rekrutiert den linken primär motorischen Kortex (M1), während Beurteilungen der Dichte Aktivitäten im linken ventralen prämotorischen Kortex (vPM) zur Folge haben (Chouinard, Large, Chang & Goodale, 2009).

Auch wenn die Ergebnisse von fMRT- und TMS- Studien zu teilweise recht unterschiedlichen Aussagen kommen, lässt sich zusammengefasst doch sagen, dass die linke Hemisphäre eine übergeordnete Rolle beim Greifen und Heben von Objekten zu spielen scheint.

Griffkraftantizipation nach Hirnschädigung

Neben den Studien mit Hilfe funktionell bildgebender Verfahren liefern Untersuchungen von Patienten nach Hirnschädigung wichtige Hinweise zu den neuronalen Substraten, welche in Greif- und Hebevorgänge involviert sind. Der häufigste Grund für lokal begrenzte, erworbene Hirnschäden ist der Schlaganfall. In Deutschland ereignen sich pro Jahr ca. 262 000 Schlaganfälle , Stand 2008, Arbeitsgemeinschaft Deutscher Schlaganfallregister (Heuschmann et al., 2010). Der Schlaganfall endet in 5-25% der Fälle tödlich und ist damit nach kardiovaskulären Ursachen und Krebs die dritthäufigste Todesursache. Seit den 60ziger Jahren geht die Sterblichkeit kontinuierlich zurück, was einen erhöhten Rehabiliationsbedarf zur Folge hat (http://www.neuro24.de/schlag.htm). Der Schlaganfall ist somit der häufigste Grund für eine erworbene körperliche Behinderung (Johnston, Mendis & Mathers, 2009). Drei Monate nach dem Ereignis leiden 25% der insgesamt Betroffenen unter schweren Einschränkungen in den Aktivitäten des täglichen Lebens, welche mit einem Barthel-Index < 60 definiert sind (Heuschmann et al., 2010; Ward, Payne, Caro, Heuschmann & Kolominsky-Rabas, 2005), ca. 17% haben mittelschwere bis schwere Funktionseinschränkungen (Heuschmann et al., 2010; Schneider, Heise, Heuschmann & Berger, 2009). Neben den motorischen Einschränkungen durch beispielsweise eine Halbseitenlähmung ist der Alltag häufig auch durch defizitäre kognitive Bewegungsplanung eingeschränkt (Unsal-Delialioglu, Kurt, Kaya, Culha & Ozel, 2008a, 2008b). Da der Schlaganfall eine häufige Erkrankung mit schwerwiegenden Folgen für die Betroffenen ist, sind klinische Studien an Patienten aus zweierlei Hinsicht bedeutsam. Zum einen helfen sie uns, die neuronalen Substrate, welche für die Griffkraftskalierung im Alltag entscheidend sind, zu finden. Zum anderen, und dies ist von besonderer Wichtigkeit, helfen sie uns, Defizite von Patienten besser zu verstehen und somit zu rehabilitieren. Da defizitäre Bewegungsplanung beide Hände betrifft, sind beispielsweise Patienten mit Halbseitenlähmung auch mit der vermeintlich besseren Hand deutlich eingeschränkt. Durch das Wissen um fehlerhafte Bewegungsplanung können wir die Defizite der Patienten bei Aktivitäten des alltäglichen Lebens besser verstehen und somit in der Therapie besser darauf eingehen.

Studien zu Griffkraftskalierung nach Schlafanfall sind bisher selten. Die wenigen Arbeiten auf Gruppen- und Einzelfallebene zeigen, dass bei einigen Patienten mit kortikaler Läsion eine Beeinträchtigung der antizipativen Kraftskalierung für neutrale Objekte unterschiedlicher Größe vorliegen kann. Eine Arbeit untersuchte Patienten mit kortikaler Läsion nach Schlaganfall. Diese antizipierten das Objektgewicht beim Heben von Boxen unterschiedlicher Größe in derselben Weise wie die gesunde Kontrollgruppe, dieses Ergebnis war unabhängig von der Seite der Läsion (Li et al., 2011). Allerdings werden in dieser Studie auch Einzelfälle beschrieben, welche eine eingeschränkte Antizipationsfähigkeit beim Heben von Boxen nach linkshemisphärischer posteriorer Schädigung zeigen (Li et al., 2007, 2011). Passend zu den oben genannten Studienergebnissen aus der funktionellen Bildgebung, finden sich auch bei Patientenstudien einige Hinweise, dass die linke Hemisphäre beim Greifen und Heben von Objekten eine übergeordnete Rolle spielt. Patienten mit linksseitigem Schlaganfall können im Vergleich zu Gesunden das Gewicht von farblich markierten Objekten nur eingeschränkt antizipieren. Patienten bei rechtsseitiger Läsion hingegen waren bei dieser Aufgabe nicht eingeschränkt. In dieser Studie hoben Patienten jeweils mit der weniger betroffenen, ipsiläsionalen Hand. Im selben Versuch mit der kontraläsionalen Hand waren beide Gruppen eingeschränkt, was wohl auf die Parese zurück zu führen ist (Bensmail, Sarfeld, Ameli, Fink & Nowak, 2012).

Im Fokus der meisten Arbeiten zu Griffkraftskalierung standen Patienten nach Schlaganfall, da dies eine sehr häufig Erkrankung ist. Des Weiteren gibt es Studien, die Patienten mit neurodegenerativen Erkrankungen untersuchten. Patienten mit isolierter Kleinhirndegeneration produzieren ähnliche Griffkräfte wie die Kontrollgruppe beim ersten Heben von jeweils einem kleinen und einem großen Gegenstand (Rabe et al., 2009). Das Kleinhirn dürfte daher bei der Griffkraftantizipation während des Hebens neutraler Objekte und der damit verbundenen Repräsentation interner Modelle keine hoch bedeutsame Rolle spielen.

In einer Studie Patienten mit Morbus Parkinson ist die die Fähigkeit zur Antizipation erhalten (Ingvarsson, Gordon & Forssberg, 1997), allerdings ist die Fallzahl mit 10 Patienten etwas gering. Nachdem Morbus Parkinson eine Erkrankung in den Basalganglien ist, erscheint ein Fallbericht von einem Patienten, der nach einem Schlaganfall in den Basalganglien unter eingeschränkten Antizipationsfähigkeiten litt (Dubrowski, Roy, Black & Carnahan, 2005), etwas widersprüchlich.

Wie auch bei den Studien mit bildgebenden Verfahren untersuchen die Patientenstudien zumeist das Greifen und Heben von abstrakten Objekten. Es gibt jedoch zwei Ausnahmen. Zum einen gibt es eine Studie mit Kindern, die unter infantiler Zerebralparese leiden. Hier zeigte sich, dass die Kinder mit der betroffenen Seite im Vergleich zur Kontrollgruppe keine Einschränkungen haben (Duff & Gordon, 2003). Jedoch sollte erwähnt werden, dass hier lediglich die Lastkraft erhoben wurde. Aus der ersten Studie der vorliegenden Dissertation wissen wir jedoch, dass die Lastkraft der weniger valide Parameter ist, wenn Aussagen zur antizipativen Griffkraftkontrolle getroffen werden sollen. Dennoch lässt sich folgern, dass Kinder mit Zerebralparese und Hemiplegie ihre Defizite im Laufe der Jahre besser kompensieren konnten als die von uns untersuchten Erwachsenen, deren Ereignis noch nicht so lange zurücklag. Interessanterweise leiden Kinder mit Zerebralparese beim Heben von neutralen bzw. neuen Objekten im Vergleich zu gesunden Kindern durchaus unter eingeschränkter Antizipationsfähigkeit, was jedoch nach einigen Übungsdurchgängen kompensiert werden kann (Duff & Gordon, 2003; Gordon & Duff, 1999). Zusammengefasst gehen wir davon aus, dass die Kinder durch täglichen Kontakt mit Alltagsgegenständen interne Repräsentationen im assoziativen Gedächtnis speichern. Sie heben im Alltag mit der weniger betroffenen Hand, jedoch wird das erworbene Wissen generalisiert mit beiden Händen angewandt. Dies konnte in Studien mit gesunden Probanden wiederholt gezeigt werden (Gordon & Duff, 1999; Gordon, Forssberg & Iwasaki, 1994).

Die zweite Patientenstudie, die mit Alltagsgegenständen durchgeführt wurde, untersuchte Patienten nach Apoplex. Hierbei hoben 6 Probanden mit linksseitigem

Schlaganfall Objekte des Alltags. Zwei der sechs Patienten litten zusätzlich an Apraxie. Von den sechs Patienten zeigten die beiden mit Apraxie defizitäre Antizipationsfähigkeit. Die Autoren sahen eine Korrelation zwischen eingeschränkter Antizipation und Läsionen im superioren und mittleren Temporallappen, sowie im inferioren Partiallappen (Dawson et al., 2010).

Apraxie

Apraxie ist als neuropsychologisches Syndrom definiert, bei dem die Betroffenen nicht mehr in der Lage sind, erlernte, zielgerichtete Bewegungen auszuführen und dies nicht durch primär sensorische oder motorische Störung zu erklären ist (Buxbaum & Permaul, 2001; De Renzi, Faglioni, Lodesani & Vecchi, 1983; Frey, 2007; Heilman, Rothi & Valenstein, 1982; Kimura, 1982; Liepmann, 1908; Morlaas, 1928; Rizzolatti & Matelli, 2003; Sirigu et al., 1995). Apraxie tritt vor allem nach Schädigungen in der linken Hirnhälfte auf und führt zu defizitärer Bewegungsplanung, folglich sind diese Patienten auch mit der weniger betroffenen Hand eingeschränkt. Etwa 25% der Patienten mit linkshemisphärischem Schlaganfall sind davon betroffen (Poeck, 1997). Man unterscheidet 3 Subtypen, die zusammen, aber teilweise auch unabhängig voneinander auftreten können. Gemeinsam ist allen drei Subtypen, dass sie jeweils nach linkshirniger Schädigung auftreten (Goldenberg, 2009). Zum einen ist die Imitation von bedeutungslosen Gesten eingeschränkt. Davon unterscheidet sich der Subtyp, bei dem bedeutungsvolle Gesten eingeschränkt sind. Hier sind Patienten nicht in der Lage, Objektgebrauch pantomimisch zu imitieren (beispielsweise wie ein Hammer benutzt wird). Patienten können im tatsächlichen Gebrauch von Objekten ebenfalls beeinträchtigt sein. Jedoch verbessern sie sich im Vergleich zur pantomimischen Leistung signifikant (Hermsdörfer, Li, Randerath, Goldenberg & Johannsen, 2012; Randerath, Goldenberg, Spijkers, Li & Hermsdörfer, 2011; Sunderland, Wilkins & Dineen, 2011). Bei diesem dritten Subtyp der Apraxie, bei dem der tatsächliche Objektgebrauch gestört ist, wissen die Patienten beispielsweise nicht, wie eine Zahnbürste zu benutzen ist und sind somit im Alltag am meisten eingeschränkt. Gerade bei diesem Subtyp stellt sich uns die Frage, ob Patienten, die nicht wissen, wie man ein Objekt gebraucht, auch dessen physikalische Eigenschaften nicht mehr einzuschätzen wissen.

In einigen Fällen ist bereits die Greifbewegung für die Werkzeugaufnahme beeinträchtigt (nicht-funktionelles Greifen). Nicht-funktionelles Greifen von Gegenständen ist von gestörtem Objektgebrauch zu unterscheiden, auch lassen sich mittels Läsionsanalysen unterschiedliche Schwerpunkte bezüglich der Infarktareale nachweisen (Randerath, Goldenberg, Spijkers, Li & Hermsdörfer, 2010). Patienten mit gestörtem Objektgebrauch hatten hauptsächlich Läsionen im linken Supramarginalgyrus, während gestörtes (nicht-funktionelles) Greifen nach Objekten mit Läsionen im linken inferioren Frontalkortex und im linken Gyrus angularis korrelierte.

Da auch bei unserer Aufgabe Objekte manipuliert wurden, stellte sich die Frage, ob eingeschränkte Antizipation der Griffkraft mit Apraxie korreliert. Alternativ dazu ist es möglich, dass beide Fähigkeiten, die antizipative Kraftskalierung sowie Leistungen in den Apraxie-Tests, Teil eines kognitiv-motorischen Netzwerks in der linken Hirnhälfte sind, aber keine direkten Überschneidungen zeigen.

Fragestellung und Methode

Im Fokus der vorliegenden Arbeit liegt die Fähigkeit, Objekteigenschaften im alltäglichen Leben einschätzen und folglich die nötige Griffkraft antizipieren zu können. Im ersten Teil wurden 11 gesunde Probanden aufgefordert, 12 Objekte des alltäglichen Lebens zu greifen und hochzuheben. Die Objekte waren in Paaren angeordnet, die Objekte eines Paares waren gleich groß, unterschieden sich aber deutlich im Gewicht. Beispielweise bildeten ein Buch und eine Packung Kaffeefilter ein Paar. Dabei stellte sich uns die Frage, inwieweit die Objektidentität und nicht allein die Objektgröße die initiale Griffkraft beeinflussen. Um dies zu differenzieren, hoben die Probanden die Objekte zuerst in einheitliches Papier verpackt und anschließend unverpackt. Neuartig an dieser Arbeit ist, dass neben der üblichen Lastkraft die Griffkraft per se gemessen wurde. Dazu wurden an den Enden der ersten drei Finger flexible Griffkraftsensoren befestigt und mittels Fingerkappen von Latexhandschuhen befestigt. Zusätzlich standen die Objekte auf einer Waage, mit deren Hilfe die Lastkraft ermittelt wurde. Die Objekte wurden mit dem Präzisionsgriff zügig hochgehoben, für 5 sec in der Luft gehalten und anschließend auf die Waage zurückgestellt.

A: 12 Objekte, in Paaren gleicher Größe unterschiedlichen Gewichts angeordnet

B: Griffkraftsensoren an den an den Fingerkuppen mit Latexhandschuhen fixiert.

Unsere Hypothese lautete, dass ein Erkennen der Objekte im Vergleich zur Versuchsbedingung, unter der die Objekte eingepackt waren, eine bessere Antizipation der Griffkraft zur Folge hat und dadurch die Griffkraftrate im Moment des Zupackens (bereits vor dem Abheben) an das Objektgewicht angepasst ist. Demzufolge wird eine Korrelation bzw. ein etwa linearer Zusammenhang zwischen Indikatoren der Fingerkräfte und den Objektgewichten erwartet. Für die Bedingung, in der die Objekte in Papier gepackt waren, war unsere Hypothese, dass die Parameter Griffkraftrate und Lastkraftrate mit dem Objektgewicht nicht korrelieren.

Die zweite Studie untersuchte 26 Patienten nach unilateraler Hirnschädigung im Rahmen eines Schlaganfalls. Alle Patienten wurden im Krankenhaus Bogenhausen akquiriert und waren mit der Teilnahme an der Studie einverstanden. Es wurden die gleichen Gegenstände gehoben, wieder wurden Griffkraft und Lastkraft ermittelt. Im Gegensatz zur ersten Studie hoben die Patienten nur in der unverpackten Bedingung. Wir unterschieden zwischen der Gruppe RBD mit rechtshirnigem Defekt und der Gruppe LBD mit linkshirnigem Defekt. Die Ergebnisse wurden mit den Ergebnissen aus den jeweiligen Kontrollgruppen verglichen. Da die Patienten immer mit der weniger betroffen, ipsiläsionalen Hand die Objekte hoben, unterschieden wir zwei Kontrollgruppen. Die eine Gruppe hob mit der linken Hand (CL) und die andere Gruppe mit der rechten Hand (CR). Alle Teilnehmer der gesamten Studie waren Rechtshänder. Um eingeschränkte Griffkraftantizipation mit Apraxie korrelieren zu können, wurden zusätzlich drei Apraxie-Tests erhoben. Zum einen testeten wir die pantomimische Imitation von Werkzeuggebrauch sowie bedeutungslose Hand- und Fingerimitation. Um die neuronalen Korrelate besser eingrenzen zu können, welche es uns im Alltag ermöglichen, Objekteigenschaften abzuschätzen und Griffkraft antizipieren zu können, fertigten wir mit Hilfe der vorliegenden cMRTs eine Läsionsanalyse (siehe auch http://www.sph.sc.edu/comd/rorden/, Randerath et al., 2010) an. Basierend auf den Erkenntnissen, dass die linke Hemisphäre für geschickte Interaktion zwischen Hand und Objekten eine große Rolle spielt, lautete unsere Hypothese, dass Patienten mit Apoplex der linken Hemisphäre im Vergleich zu Gesunden Objekteigenschaften im Alltag nur eingeschränkt antizipieren können und die initiale Griffkraft somit nicht mit dem Objektgewicht korreliert. Wir gingen davon aus, dass zwischen Patienten mit Apoplex der rechten Hemisphäre und der Kontrollgruppe kein Unterschied ist.

Eigenanteil der vorliegenden Arbeit

Die Doktorandin hat die vorliegenden Daten im Krankenhaus Bogenhausen und den Räumlichkeiten der Entwicklungsgruppe Klinische Neuropsychologie komplett selbst erhoben und im Anschluss ausgewertet. Die Vorbereitung für die Studie erfolgte in Zusammenarbeit mit Prof. Dr. Joachim Hermsdörfer.
Prof. Dr. Goldenberg, emeritierter Chefarzt der Neuropsychologie im Krankenhaus Bogenhausen, half bei der Akquise und Auswahl der Studienteilnehmer mit unilateralem Hirnschaden. Dr. Jennifer Randerath unterstützte bei der Läsionsanalyse. Beide Veröffentlichungen wurden zunächst durch die Doktorandin selbst verfasst und im Anschluss in Zusammenarbeit mit Prof. Dr. Joachim Hermsdörfer in die endgültige Form gebracht. Der Coautor Dr. Yong Li Coautor stand als Programmierer der Griffkraftmessung (Technik Novel) bei technischen Fragen für den Methodenteil unterstützend zur Seite.

Zusammenfassung

Ziel dieser Arbeit ist es, antizipative Griffkraftskalierung beim Heben von Alltagsgegenständen zu untersuchen. Während in früheren Studien das Greifen und Heben von abstrakten Gegenständen untersucht wurde, dienten hier Alltagsgegenstände als Objekte. Unser tägliches Leben ist von Objektmanipulation dominiert. Die Fähigkeit, Objekteigenschaften einschätzen und die notwendige Griffkraft antizipieren zu können, ermöglicht uns geschmeidigen und effizienten Objektgebrauch. Wir untersuchten antizipative Griffkraftskalierung in zwei Studien mit unterschiedlichen Probanden: zum einen junge, gesunde Probanden (Studie 1) und Patienten mit unilateralem Hirnschaden nach Schlaganfall (Studie 2). Während sich die erste Studie mit grundsätzlichen Prinzipien der Griffkraftskalierung im Alltag beschäftigte, untersuchte die zweite Studie den Einfluss unilateralen Hirnschadens darauf. Zu diesem Zweck hoben die Probanden unterschiedliche Alltagsgegenstände mit einer breiten Gewichtspanne. In Studie 1 hoben elf gesunde Probanden die Objekte unter zwei unterschiedlichen Bedingungen. Im ersten Durchgang waren die Objekte mit einheitlichem Papier verpackt, so dass die Objektidentität nicht zu erkennen war. Dabei wurde sowohl die Griffkraft mit Hilfe von Sensoren an den Fingerkuppen, als auch die Lastkraft mit Hilfe einer Waage ermittelt. Aus den Daten des ersten Durchgangs ohne Verpackung der Objekte wurde ersichtlich, dass das Objektgewicht antizipiert und die Griffkraft entsprechend skaliert wurde. Die maximale Griffkraftrate während des Kraftanstieges erwies sich als reliabelster Parameter um zu beweisen, dass das Objektgewicht tatsächlich antizipiert wurde. Andere Messungen zeigten auch antizipatives Heben, wenn die Objektidentität verborgen war. Im Verlauf des Hebevorgangs, vor allem nach dem Abheben, verbesserte sich die Linearität zwischen Kraft und Gewicht, vermutlich mit Hilfe sensorischer Informationen. Ein zweiter und dritter Hebevorgang mit demselben Objekt führte zu keiner signifikanten Verbesserung der Präzision, mit welcher gegriffen wurde.

Ziel von Studie 2 war zu untersuchen, ob eine Schädigung der linken Hemisphäre zu eingeschränkter antizipativer Griffkraftkontrolle beim Heben von Alltagsgegenständen führt. Zu diesem Zweck wurden Daten von 26 Patienten des Klinikums Bogenhausen nach unilateraler Hirnschädigung (16 Patienten nach linksseitigem, 10 Patienten nach rechtsseitigem Schlaganfall), sowie 21 gesunde Kontrollprobanden erhoben. Apraxie wurde mit Hilfe unterschiedlicher, etablierter Tests (pantomimischer Werkzeuggebrauch, Imitation von bedeutungslosen Finger- und Handstellungen) diagnostiziert. Die Objekte waren dieselben wie in der ersten Studie, wieder wurde mit Hilfe von Sensoren an den Fingern die Griffkraft erhoben. Auch hier wurde die maximale Griffkraftrate als reliabler Parameter für antizipative Leistung ermittelt. Durch Regressionsanalysen konnte gezeigt werden, dass ein Schlaganfall in der linken Hemisphäre zu deutlicher Einschränkung der antizipativen Fähigkeit und Griffkraftskalierung führt. Patienten mit Schlaganfall in der rechten Hemisphäre zeigten im Vergleich mit der Kontrollgruppe keine defizitäre Griffkraftkontrolle. Die Läsionsanalyse zeigte, dass Läsionen im linken inferioren Frontalhirn und im linken prämotorischen Kortex zu eingeschränkter prädiktiver Griffkraftkontrolle im Alltag führen. Interessanter Weise sind das Bereiche, welche auch mit Objektmanipulation assoziiert werden. Weiter zeigten sich auch Korrelationen zwischen pathologischen Apraxie-Tests und eingeschränkter Griffkraftantizipation. Jedoch korrelierten nicht alle Tests, was für unabhängige Prozesse spricht. Zusammengefasst scheint es so zu sein, dass die linke Hemisphäre im Allgemeinen für antizipative Griffkraftskalierung im Alltag eine große Rolle spielt. Die neuronalen Substrate scheinen nicht auf eine Region beschränkt zu sein, vielmehr scheint entscheidend zu sein, dass das Netzwerk der linken Hemisphäre ungestört arbeiten kann. Da die linke Hemisphäre auch für Objektmanipulation dominant ist, sind die Überschneidungen vermutlich so zu erklären.

Abstract

The aim of this dissertation was to investigate anticipatory grip force scaling when lifting everyday objects. Previous studies were mostly restricted to lifting and grasping of neutral objects. In this study participants lifted everyday objects when grip force was registered. Our routine of everyday life is dominated by object manipulation. The ability to estimate objects properties and anticipate the grip force to grasp and lift the object promotes smooth and efficient object manipulation. We investigated anticipatory grip force scaling when lifting everyday objects in two different samples: healthy subjects (study 1) and patients with unilateral brain damage after stroke (study 2). While the first study reveals basic principles of grip force scaling in healthy young adults, the second study evaluates the effects of brain damage.

For this purpose, different objects of everyday life with a wide range of weight were handled. In study 1 eleven healthy subjects lifted 12 objects under two different conditions. In the first trial, the objects were wrapped with paper to obscure the identity of the objects. Grip force was measured by force sensors taped on the fingertips. In addition, load force was measured by the means of a scale. Data from the first lift under the unwrapped condition confirmed that participants anticipated an object's weight and scaled their grip force correspondingly. The maximum grip force rate at the force increase phase was identified as the most reliable measure to verify that object weight was predicted. Other force measures like maximum load force rate were not as reliable, they were scaled to object weight also when object identity was not known. Variability and linearity of the relationship between grip force and weight improved during the lifting, assumably with the help of sensory information. A second and third trial with the same object in a separate block did not refine the accuracy of the grip force scaling. The aim of study 2 was to investigate whether left brain damage impairs anticipatory force scaling when lifting everyday objects. Therefore, we examined 26 patients with unilateral brain damage (16 with left brain damage, ten with right brain damage) and 21 healthy control subjects. Different tests, like pantomime of familiar tool-use and imitation of meaningless hand postures, assessed

limb apraxia. The objects were equal to the first study, once again grip force was measured with the help of sensors taped on the fingertips. Again, the maximum grip force rate thought to be the most reliable parameter for anticipatory grip force scaling was determined. Regression analysis showed a clear deficit of anticipatory grip force scaling for the group with left- hemisphere stroke. The group with stroke of the right hemisphere yielded non impaired force scaling compared with the control group. Lesion-analyses indicate that stroke in the left inferior frontal gyrus (IFG) and the premotor cortex (PMC) causes the described deficits. Interestingly, these are the same structures which are associated with object manipulation. Further, significant correlations of impaired anticipation with limb apraxia scores were found. However, also dissociations between the tests of limb apraxia und impaired grip force anticipation emerged, which implicates independent processes. Summarized, our findings implicate that the underlying neural substrate is not restricted to a single region; rather it may rely on the intact left hemisphere network. Overlapping is presumably explained as the left hemisphere dominantes tool use either.

Veröffentlichung I

Exp Brain Res (2011) 212:19Ð31
DOI 10.1007/s00221-011-2695-y

RESEARCH ARTICLE

Anticipatory scaling of grip forces when lifting objects of everyday life

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Received: 22 February 2011 / Accepted: 7 April 2011 / Published online: 4 May 2011

Abstract The ability to predict and anticipate the mechanical demands of the environment promotes smooth and skillful motor actions. Thus, the Þnger forces produced to grasp and lift an object are scaled to the physical properties such as weight. While grip force scaling is well established for neutral objects, only few studies analyzed objects known from daily routine and none studied grip forces. In the present study, eleven healthy subjects each lifted twelve objects of everyday life that encompassed a wide range of weights. The Þnger pads were covered with force sensors that enabled the measurement of grip force. A scale registered load forces. In a control experiment, the objects were wrapped into paper to prevent recognition by the subjects. Data from the Þrst lift of each object conÞrmed that object weight was anticipated by adequately scaled forces. The maximum grip force rate during the force increase phase emerged as the most reliable measure to verify that weight was actually predicted and to characterize the precision of this prediction, while other force measures were scaled to object weight also when object identity was not known. Variability and linearity of the grip forceÐweight relationship improved for time points reached after liftoff, suggesting that sensory information reÞned the force adjustment. The same mechanism seemed to be involved with unrecognizable objects, though a lower precision was reached. Repeated lifting of the same object within a second and third presentation block did not improve the precision of the grip force scaling. Either practice was too variable or the motor system does not prioritize the optimization of the internal representation when objects are highly familiar.

Keywords Sensorimotor control · Anticipation · Grasping and lifting · Grip force · Internal model

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Introduction

Skilled and economical object manipulation relies on our ability to anticipate the physical properties of the objects we are interacting with. If the motor system had to rely solely on sensory input and feedback mechanism, motor execution would be slowed and awkward.

A fundamentally relevant object property when scaling grip forces and lift forces is weight. It has been shown that the grip force anticipates objects weight already before it lifts off and consequently before the weight can be inferred from sensory signals (Johansson and Westling 1988). This mechanism requires prior information about the weight. A strong predictor of weight and other physical object properties comes from the preceding trial when the same object is lifted consecutively (Johansson and Westling 1988; Witney et al. 2000; Flanagan et al. 2001). Information about the relevant object properties can also be inferred from visual cues. A particularly important cue is the size of the object, which enables an estimation of the weight when the material is known. It has been frequently demonstrated that grip and load forces indeed anticipate object size (Gordon et al. 1991a, b; Cole 2008; Li et al. 2009). In addition to size, object material can inform about weight and influences early force production (Buckingham et al. 2009; Flanagan and Wing 1997; Flanagan et al. 1995).

Apart from weight, other physical object characteristics determine the grip force necessary to hold an object. Thus, friction at the finger–object contact is crucial and it has been shown that changes in the objects surface material with altering friction are precisely anticipated on the basis of the last lifting trial (Cadoret and Smith 1996; Flanagan and Johansson 2002; Johansson and Westling 1984). Other relevant object characteristics are the form and the size of grasped object that determine the mechanical stability of the grip. However, not every cue is effective to scale grip forces. For example, an instructional visual cue indicating an eccentric center of mass is not effective to partition grip force adequately between the grasping fingers to avoid object tilt (Salimi et al. 2003). Similarly, knowledge about weight loss due to half emptying a glass of water with a straw did not lead to decreased initial grip force production during the first lifting of the glass after drinking (Nowak and Hermsdörfer 2003b). In cases of inappropriate initial force scaling, fast control mechanisms ($\leq$100 ms) based on sensory afferent information corrected the force output, so that the appropriate force level is achieved already during the actual lifting trial (Johansson and Westling 1987; Johansson and Edin 1993; Johansson and Flanagan 2009).

In the above examples, knowledge about the relationship between object properties and necessary grip force is acquired over a long time by daily experience (Flanagan and Johansson 2009; Flanagan et al. 2008). Experiments have also investigated the learning of relationships between abstract cues and object properties. Thus, an association between the color of a grasped object and the weight can quickly be learned (Cole and Rotella 2002), and the memory is retained for at least 24 h, with only a modest decrease in precision in the anticipatory force scaling (Nowak et al. 2007a; Gordon et al. 1993). Similarly, color or acoustic cues presented before lifting were successfully used for grip force scaling (Ameli et al. 2008).

The various findings of successful anticipation during manipulation of neutral objects lead to the expectation that also the properties of objects manipulated during daily life are anticipated. However, there are only few studies that have investigated finger force control during grasping and lifting of everyday objects, and there is no study yet that has measured the grip forces. Gordon and colleagues (Gordon et al. 1993) registered the load force during the grasping and lifting of differently heavy objects such as package of crisp bread, a beer can, and a telephone book, by using a scale. They evaluated the maximum load force rate and the time from finger contact until liftoff. Both measures yielded characteristic variations with the object, indicating that physical characteristics were considered in the load force production already before the object was lifted from the table and weight information was available to the subjects. Importantly, this scaling was obvious from the first lift, although some adjustments occurred during successive lifts of the same objects. Comparable findings were reported in a study of healthy children and children affected by cerebral palsy (Duff and Gordon 2003) and in a study in left brain damaged patients (Dawson et al. 2010). In the later study, two patients with apraxia did not show a clear scaling of load force production with object identity. From the findings in healthy subjects, it was concluded that early load force production anticipates object weight by recognizing the object's identity and associating the information about relevant physical properties.

The above experiments were limited to load force measurements. The obvious reasons were mainly technical. Everyday objects cannot easily be equipped with force sensors without changing the object characteristics and exactly defining the point of force insertion. However, this limitation could pose problems. First, focusing on the load force may not allow generalization to anticipatory control of grip forces. For example, the influence of sensorimotor memory from the previous force production may differ for grip and load force (Cole 2008; Quaney et al. 2003). In addition, grip and load force anticipation may underlie partly different neural representations as suggested by normal anticipation of object size in grip force but unprecise anticipation in load force in patients with cerebellar disease (Rabe et al. 2009). Another problem may arise from the mechanical fact that the range of load forces that can be produced during lifting of a certain object is limited by the object's weight. The grip force on the other hand can be arbitrarily high, as long as the object's material provides resistance and the subject's individual maximum is not reached. To overcome the restriction of pure load force measurement using a scale, we additionally introduced a method that enabled the measurement of grip force during lifting of everyday objects. To this aim, flexible force sensors were wrapped around the distal pads of the grasping fingers. We hypothesized that early grip force production is scaled to the known weights of the objects as already suggested by the measurements of load force in earlier studies.

In addition to investigating the lifting of everyday objects with known identity, we blocked object knowledge during lifting in a separate condition. To this aim, the objects were wrapped in paper so that their identity could not to be inferred. In this way, the effect of knowledge on anticipatory force scaling could be separated from other potentially relevant factors such as object size and rigidity. In addition, it was possible to analyze the effectiveness of sensory mechanisms after object liftoff with and without object knowledge. It was hypothesized that the benefit of prior knowledge for the precision of anticipation is still obvious when after liftoff the grip force maximum is reached.

As indicated earlier, the repetitive lifting of everyday objects resulted in a further optimization of the load forces (Gordon et al. 1993). This procedure, however, left open whether this improvement was due to sensory motor memory from the previous lift or from a more precise memory representation of the object. In an attempt to test the role of practice without the confound of repetitive lifting, we studied object lifts followed and preceded by different objects. In particular, a whole set of twelve objects was lifted before a certain object reappeared. We hypothesized that single lifts may nevertheless refine and update the memory of the object properties. If this is the case, grip forces should be better optimized for the particular object in a second and third occurrence of the same object.

The use of a relatively large set of twelve objects enabled us to quantify the precision of the anticipation of object weight by calculating linear regressions in individual subjects.

Materials and methods

Subjects

Twelve healthy subjects participated in the experiment. We excluded one female subject who produced excessive forces (more than 5 SD higher than the group mean) from the analysis, leaving eleven subjects (5 women, 6 men) with a mean age of 26.5 years (SD 6.0 years). None of the subjects had any history of neurological diseases or any movement restriction of the hand or arm. All subjects were right-handed according to self-report. The study design was approved by the ethical committee of the Medical Faculty of the Technical University of Munich. Informed consent was obtained from all subjects, and the study was conducted in accordance with the Declaration of Helsinki.

General task

The general task of the subjects was to grasp and lift everyday objects. Subjects sat at a table, with the dominant right-hand resting comfortably on the table approximately 20 cm right from the body midline. A scale with a platform (diameter 25 cm, 5 cm above the table top) was placed in a comfortable reaching distance (about 50% of maximal reaching distance) in front of the body. The examiner sat opposite to the subject and placed the objects on the scale. The objects were slightly rotated against the frontal plane so that they could be comfortably grasped and lifted. The instruction was to reach for the object with the right-hand, to grasp it with the thumb and the index and middle finger in opposition (three finger grip) and to lift it about 5 cm above the scale with a speedy (but not maximum fast) movement. The goal was to prevent the subject from using a probing behavior such as palpating the object before lifting. A tone indicated the start of the movement and another tone, 3.5 s later, indicated the replacement of the object back onto the scale. The subjects were requested to close their eyes during the placement of the objects to avoid any cues about object weight from the observation of the examiner's movement. After reopening of the eyes, a pause of 3 s enabled careful inspection of the object before the tone initiated the action.

Objects

Twelve objects of everyday life were selected for the task. The selection criteria included easy identification from the visual appearance, familiarity to everyone, and frequent manipulation during everyday actions, enabling a comfortable grasp. The selected objects covered a wide range of weights between 26 g (cigarette pack) and 1,060 g (milk carton). To control for potential effects of size, the objects were organized in pairs of objects with similar size but different weight. The pairs comprised the following objects: small liquor bottle–cigarette pack, plastic cup for tooth brushing–porcelain mug, candle–tea pack, spaghetti pack–biscuits, book–coffee filter, milk carton–large tissue package (see Fig. 1a). Table 1 indicates the weight and the volume of each object. The objects were placed with their longer axis oriented in the vertical direction. The objects that contained food or goods were new and unopened. This was obvious from the visual appearance, and subjects were also informed about this fact. The plastic cup and the porcelain mug were empty, and this was obvious to the subjects from their viewing position.

The objects were presented in two fundamentally different conditions. Apart from the normal viewing condition, the objects were tightly wrapped into non-transparent thick white paper in a control condition, so that the subjects could not infer the identity from the visual appearance (see Fig. 1b). This condition served to assess the effects of other factors than processing identity that may influence anticipatory force scaling and force production such as object

Fig. 1 **a** Everyday objects lifted in the experiment. The objects were organized into six pairs with similar size but different weight (condition ID+). **b** The same objects wrapped into white paper to hide object identity (condition ID−). **c** Measurement of grip forces. Flexible force-sensors arrays were applied over the pads of the thumb, the index and the middle finger and secured by rubber caps

Table 1 Weight and volume of 12 everyday objects utilized in the present experiment

	Liquor	Cigarettes	Mug	Plastic cup	Candle	Tea	Spaghetti	Biscuit	Book	Filter	Milk	Tissues
Volume (cm^3)	145	121	441	366	343	366	567	819	1,260	1,250	1,140	1,300
Weight (g)	243	26	270	70	418	36	526	214	805	154	1,060	290

Object pairs are listed next to each other

geometry or mechanical properties of the material (e.g., rigidity).

A gray plastic cylinder (diameter 75 mm, height 80 mm, weight 400 g) was used as a neutral object. It was lifted during training trials and in between each lift of an everyday object to neutralize effects from lifting of the last object on the current object (sensorimotor memory) (see Johansson and Westling 1984, 1988). Evaluation of the training trials revealed the typical decrease in the grip force to an approximately constant force level during the first four lifts. These trials were not further considered in the analysis.

Procedure

Each session started with six lifting trials of the neutral object to familiarize with the task. Then, the twelve everyday objects were lifted in succession, always interrupted by a lift of the neutral object. As indicated earlier, objects were lifted pairwise but the order of objects within a pair and the sequence of the pairs were randomized across subjects. After completion of a block of all twelve objects, second and third blocks were tested. The order of pairs differed in each block. Regular breaks of about 10 s were introduced after each lifting movement.

Both conditions were examined in each subject, the "wrapped" condition (ID−) always first and the "unwrapped" condition (ID+) after a break of minimum 2 weeks. Only rarely the subjects spontaneously reported that they recognized the object after the first session. However, none of the subjects tried to estimate object identity before lifting during this session. When interviewed after the second "unwrapped" session, all subjects commented that they are highly familiar with each of the twelve everyday objects.

Data recording

The scale was equipped with a force sensor that measured the weight force produced by the objects (accuracy ±0.1 N, sampling rate 100 Hz). Producing a load force in the upward direction decreases the sensor reading until the object lifts off. In the following, we will denote the weight signal as load force, although the true load produced by the finger acted in the opposite direction. The scale did not provide load information after liftoff. The grip force was measured using force sensor arrays applied to the pads of the distal phalanxes of the three grasping fingers. Each sensor array contained 16 force sensors, distributed across an area of 20 × 20 mm, resulting in a spatial resolution of 5 × 5 mm^2 (sensor S2001, Pliance System, Novel, Munich, Germany). The thin (0.5 mm) and flexible arrays were fixed to the finger pads by rubber caps cut from standard medical gloves (see Fig. 1c). The cables were fixed loosely to the palmar aspect of fingers and hand with a tape. The calibrated pressure range of the arrays ranged from 500 to 20,000 hPa, corresponding to 0.5–20 N/cm^2. The sampling rate amounted to 100 Hz. The sensors were zero-calibrated in the mounted position. Bending of the sensors and hysteresis could cause absolute errors of 10%. With no change of mounting within one session, the relative errors were, however, much smaller. With this configuration, grip forces could be measured during grasping arbitrary objects, however, at the expense of absent direct skin contact with the object. As obvious from our results, the sensors and the rubber caps did not impede anticipatory force scaling. For each sensor array, the total force was obtained by integrating across the pressure distribution. Finally, the three sensor forces were summed up to provide a measure of the instantaneous grip force. Note that this sum of the forces from both sides of a grasped object is twice the value resulting from normal one-sensor measurements.

Data analysis

From the time courses of the grip force and the load force, specific time points were determined for each lifting trial. The moment of contact between the fingers and the object (TGFonset) was defined as the moment when the grip force exceeded baseline variability (>0.1 N). Maximum grip force (GFmax) and the corresponding time point (TGFmax) were then detected. When on rare occasions, the grip force continued to increase after the lifting had terminated, the maximum closer to the lifting movement was considered. Between TGFonset and TGFmax, the first peak of grip force rate (GFRmax) was determined as a local maximum in the first derivative of the grip force profile. The time derivatives were obtained by means of kernel estimates (cutoff frequency 12 Hz; see Marquardt and Mai 1994). If more than one grip force rate peak occurred in the time window, the first clear peak was considered to represent the prediction of object properties, while further peaks represent corrective actions (see Johansson and Westling 1988). Consequently, the first peak was used for the analysis. The criteria was a corresponding grip force of at least 1 N and a minimum decrease in the grip force rate by at least 25% of the peak value following the peak. From the load force profile, the time of liftoff (TLFoffset) was determined as the time point just before the scale reading (inverted load force) was zero (<0.1 N). The interval between TLFoffset and TGFonset was defined as liftoff time (Tlift-off). Finally, the peak load force rate (LFRmax) was determined from the scale signal using similar criteria as for GFRmax, applied to the load force signal (no load threshold, 25% LFmax decrease).

Statistical analysis

Two statistical approaches were used to test the hypothesis that produced forces and force rates depended on the objects. In a first analysis, the grip force measures for the two objects of each pair belonging to the first block were compared within subjects with paired *t* test. In a second analysis of the first block, the relationship between all measures of each subject and corresponding object weight was graphically displayed, and the coefficient of the linear regression was calculated to express the strength of the relationship. This step led to the exclusion of two objects (see "Results"). For the remaining ten objects, linear regressions of the relationship between grip force measures and weight were calculated for each subject, each condition, and each block. The coefficient of regression, the slope, and the average levels for each fit were then entered into analyses of variance with the within-subject factors "condition" (ID−, ID+) and "block" (first, second, third). The average level of the fits was calculated by using the average weight of the ten objects in the equation of each linear regression. To test for a potential effect of objects size on the grip force production in the wrapped condition, linear regressions were calculated for the relationship between grip force rate and object volume. The level of statistical significance was set at 0.05.

Results

Figure 2 shows the profiles of the grip and load force for one subject, as well as the corresponding rates for four selected objects during their first presentation under both experimental conditions. When the objects could be visually identified, all force signals seem to be scaled to the object's weight. Grip force, grip force rate, and load force rate developed faster and obtained higher values for the heavier objects with a congruent order between signals and weight. When the objects were wrapped under the control condition, the relationship between force signals and object weight was less clear, although the grip force and the load force rate still seem to be scaled to the object's weight. These findings emerged as typical for the group.

Figure 3 shows the results for object pairs with similar size during the first block. When the objects could be viewed normally, the heavier object within each pair was grasped with a significantly higher maximum grip force rate and a higher maximum grip force. The only exception was the pair of spaghetti and biscuit packs for which maximum force rate did not differ significantly. When object identity was unknown in condition ID−, the grip force rate scaled with the object's weight for only two out of six pairs. Correct scaling was more frequent under this condition for the maximum grip force that exhibited higher values for the heavier object in four out of six pairs (the candle–tea pair failed only due to one outlier). Thus, already during the first presentation, grip force production was scaled according to the relative weight of the object in the pair when subjects knew the identity.

To analyze how the scaling of the grip and load forces was related to the absolute weight of the objects, the relationship was directly investigated. As obvious from Fig. 4, there was a general trend for a linear relationship with the exception of some objects and notable differences between conditions and measures. When object identity was known, all four measures yielded a significant relationship with the object's weight. The strength of the relationship was highest for the load force rate ($R^2 = 0.71$) and lowest for the liftoff time ($R^2 = 0.29$). Deviations from linearity were obvious for spaghetti (as had to be expected from the missing within-pair difference; Fig. 3) and for milk, obvious as relatively low maximum grip forces and grip force rates, as well as for the book, that on the contrary was grasped with relatively high grip forces and grip force rates. While in condition ID− with wrapped objects the maximum grip force rate varied independently from the object weight ($R^2 = 0.02$), a significant dependency was found for the other three measures. For the maximum grip force and the maximum load force rate, the strength of the dependency was somewhat weaker than under the condition ID+ (see Fig. 3), and for the liftoff time, the dependency was stronger.

To analyze whether object size was used as a cue to predict object weight in the absence of other salient information, we calculated the linear regression between the maximum grip force rate and object volume (see Table 1) for the trials of the first block. For the combined data (Fig. 4), the resulting fit slightly increased, but variability was very high ($R^2 = 0.035$). For the individual subjects, the regressions were non-significant in ten of the eleven cases. Only one subject seemed to have used size information for the scaling of the maximum grip force rate in the condition ID− ($R^2 = 0.37$, $P = 0.048$).

In order to directly compare the two conditions and to evaluate the effect of repeating the blocks of twelve objects, linear regressions were performed for the relationship between grip force measures and object weight for each subject, each condition, and each block. The objects spaghetti and milk that seem to violate the linear relationship (see also "Discussion") were excluded from this analysis. The resulting parameters of the linear fits are

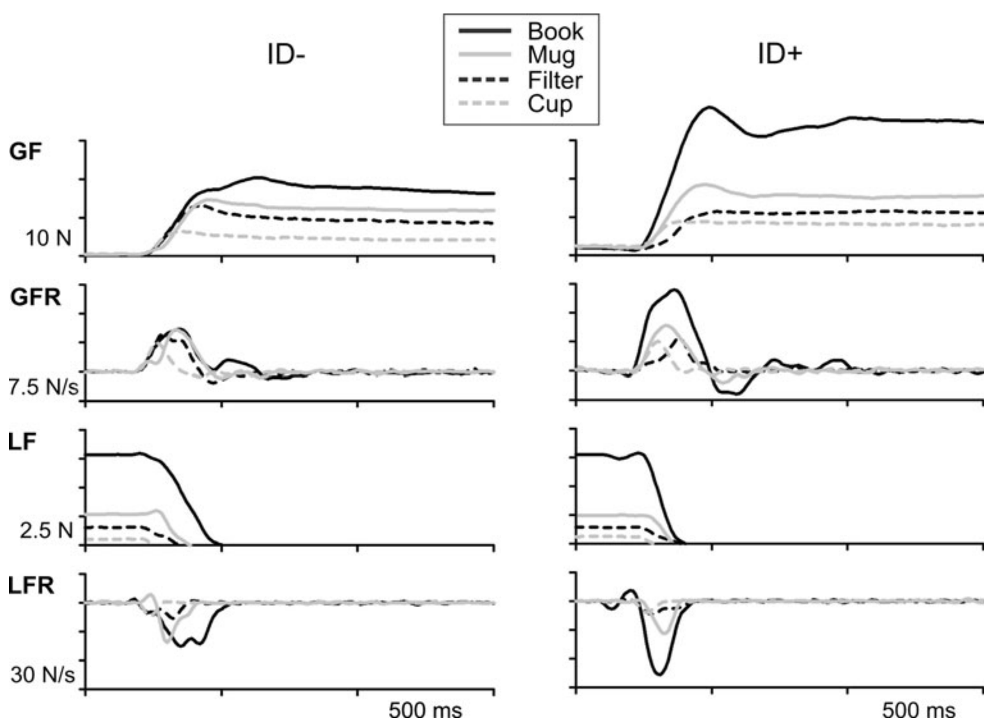

Fig. 2 Time course of the grip force (GF), grip forcer rate (GFR), load force (LF: exact: inverted isometric load force, see "Materials and methods"), and load force rate (LFR) during the first lift of two selected object pairs (book & filter, mug & plastic cup). Performance of one typical subject is shown. In condition ID+, objects could be viewed normally, while in the control condition ID−, objects were wrapped into paper and could not be identified. Objects are listed according to descending weight; a *broken line* indicates the lighter object of a pair

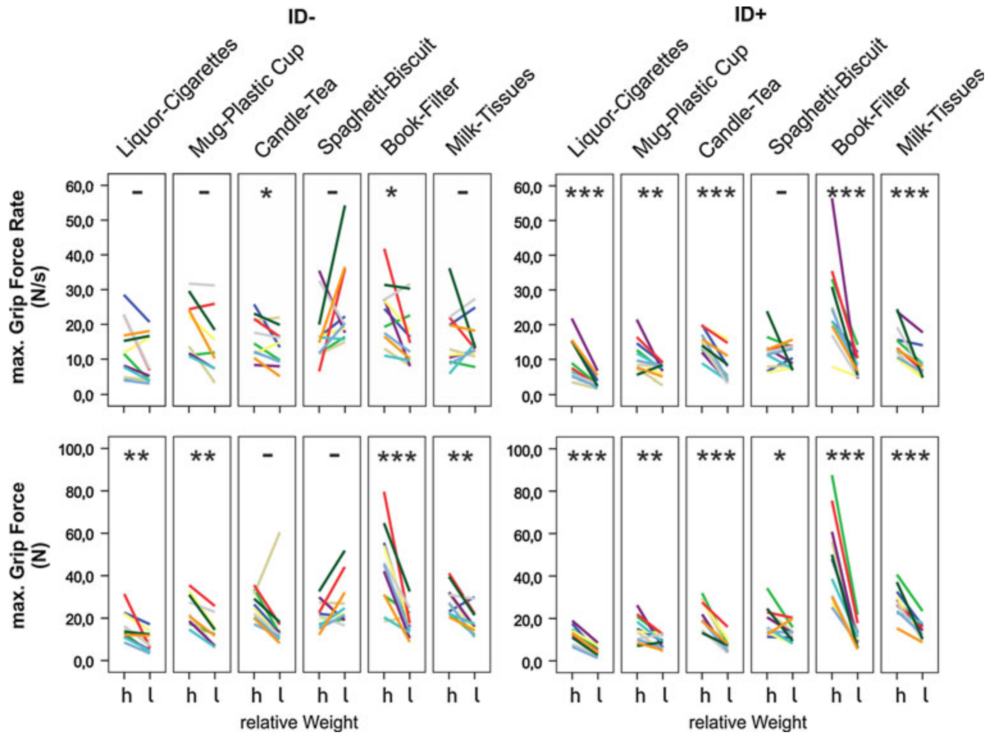

Fig. 3 Maximum grip force rate and maximum grip force during grasping and lifting 12 everyday objects organized into six pairs of relatively heavy (h) and relatively light (l) objects. Individual performance of eleven subjects in the first block for conditions ID+ and ID− is shown. Results of pairwise t test are indicated: $***P \leq 0.001$, $**P \leq 0.01$, $*P \leq 0.05$, $-P > 0.05$

displayed in Fig. 5 and were subjected to analyses of variance.

The coefficient of the linear regression R^2 clearly depended on the condition for both grip force measures (R^2-GFRmax "Condition": $F_{1,20} = 102.8$, $P < .001$; R^2-GFmax: $F_{1,20} = 13.7$, $P = .004$). The group mean of the coefficient increased across blocks, with a relatively strong numerical increase being obvious for the maximum grip force during condition ID− (Fig. 5). However, neither a significant main effect of block nor an interaction was found for the maximum grip force rate (R^2-GFRmax "Block": $F_{2,20} = 2.5$, $P > .1$, "Condition × Block": $F_{2,20} < 1$, $P > .1$). For the maximum grip force, the main effect of block just failed to reach the level of statistical significance (R^2-GFmax "Block": $F_{2,20} = 3.3$, $P = .056$; "'Block × Condition": $F_{2,20} = 1.0$, $P > .1$). Thus, the precision of the linear fit was high when object identity was known already from the first lifting without strong improvement across repeated blocks. The slope of the relationship between grip force measures and object weight was similar for the two conditions in case of the maximum grip force (Slope-GFmax "Condition": $F_{1,20} = 1.2$, $P > .1$) and did not change across the blocks for both measures (Slope-GFRmax "Block," $F_{2,20} < 1$, $P > .1$; "Condition × Block": $F_{2,20} < 1$, $P > .1$; Slope-GFmax: $F_{2,20} = 1.2$, $P > .1$; "Condition × Block": $F_{2,20} = 1{,}8$, $P > .1$). For the grip force rate, the effect of the condition was statistically significant (Slope-GFRmax "Condition": $F_{1,20} = 19.1$, $P = .001$) since the fit was close to horizontal for the ID− condition (see Fig. 4), and the corresponding slope was close to zero. To obtain an estimate of the average magnitude of each grip force measure, the mean weight of the ten objects was determined (253 g) and used in the formulas of the linear regressions. The resulting levels were significantly higher for the ID− condition than those of the ID+ condition for both measures (Level-GFRmax "Condition": $F_{1,20} = 10.8$, $P = .008$; Level-GFmax: $F_{1,20} = 7.4$, $P = .021$). In addition, the levels decreased significantly across repeated blocks irrespective of the condition (Level-GFRmax "Block": $F_{2,20} = 5.6$, $P = .012$; "Block × Condition": $F_{2,20} < 1$, $P > .1$; Level-GFmax "Block": $F_{2,20} = 11.1$, $P = .001$; "Block × Condition": $F_{2,20} = 1.7$, $P > .1$).

A descriptive comparison of the linear regressions (only first block) for the maximum grip force rate and the maximum grip force reveals a clear improvement of the fit from the maximum grip force rate, which occurs earlier in time before liftoff, until the maximum grip force, occurring after liftoff. For the coefficient of regression, the increase was stronger for the ID− condition than for the ID+ condition (ΔR^2 ID− = 0.40, ΔR^2 ID+ = 0.16; see Fig. 5). The later coefficient, however, started with much higher accuracy.

ANOVA for the maximum load force rate revealed a main effect of condition for the coefficient of linear regression, which was higher when objects could be identified (R^2-LFRmax "Condition": $F_{1,20} = 7.0$, $P = .024$; mean ID+: −0.81, ID−: −0.71; see Fig. 4 for the first block). In addition, the mean level of the maximum load

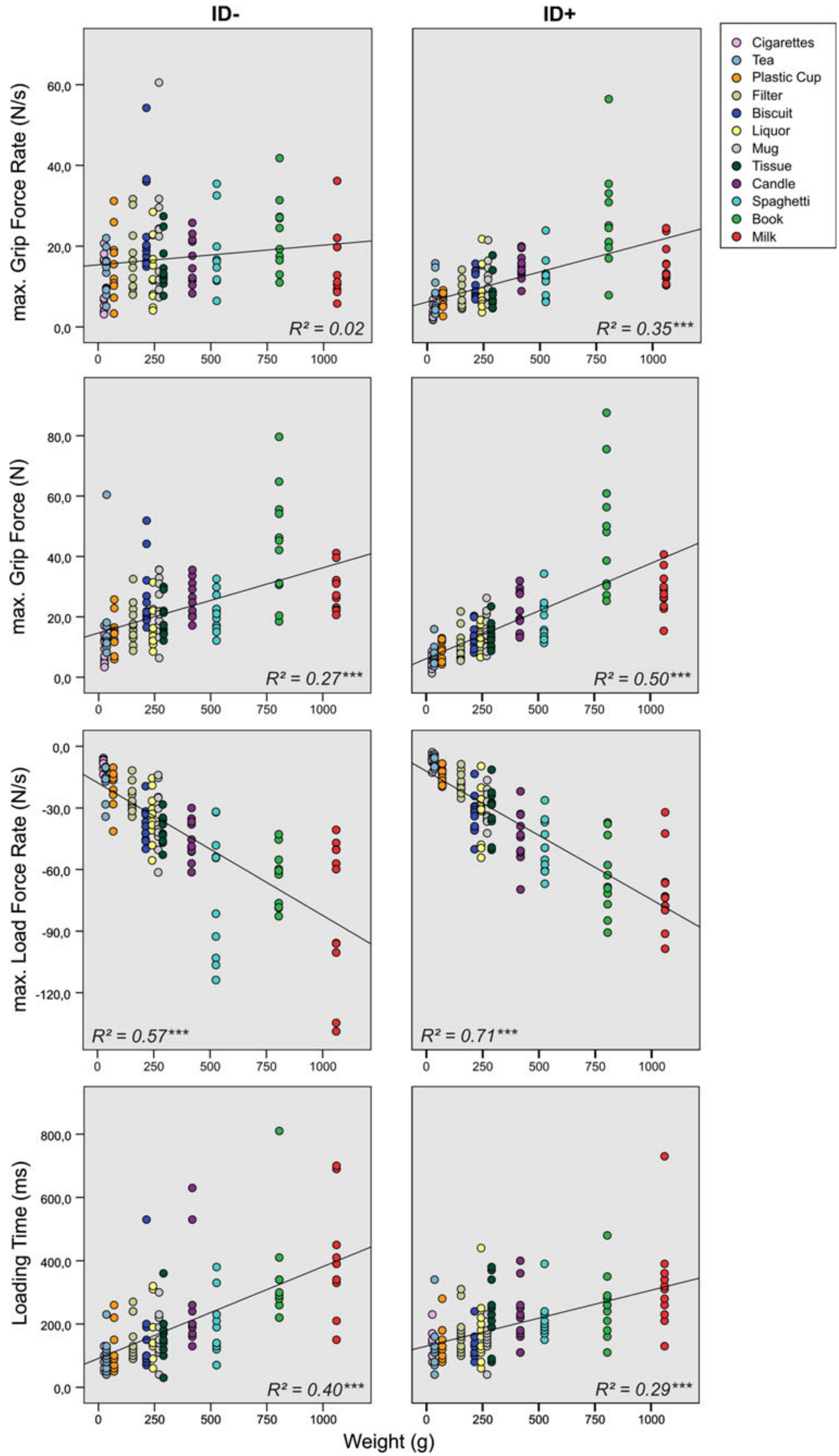

Fig. 4 Relationship between four measures characterizing force control during lifting (maximum grip force rate, maximum grip force, maximum load force rate, and liftoff time) and object weight. Results of 11 subjects for twelve objects (ordered by increasing weight) during the first block are displayed for conditions ID− and ID+. The *line* reveals the best linear fit with the coefficient of regression R^2 and statistical significance of the correlation (***$P \leq 0.001$) indicated

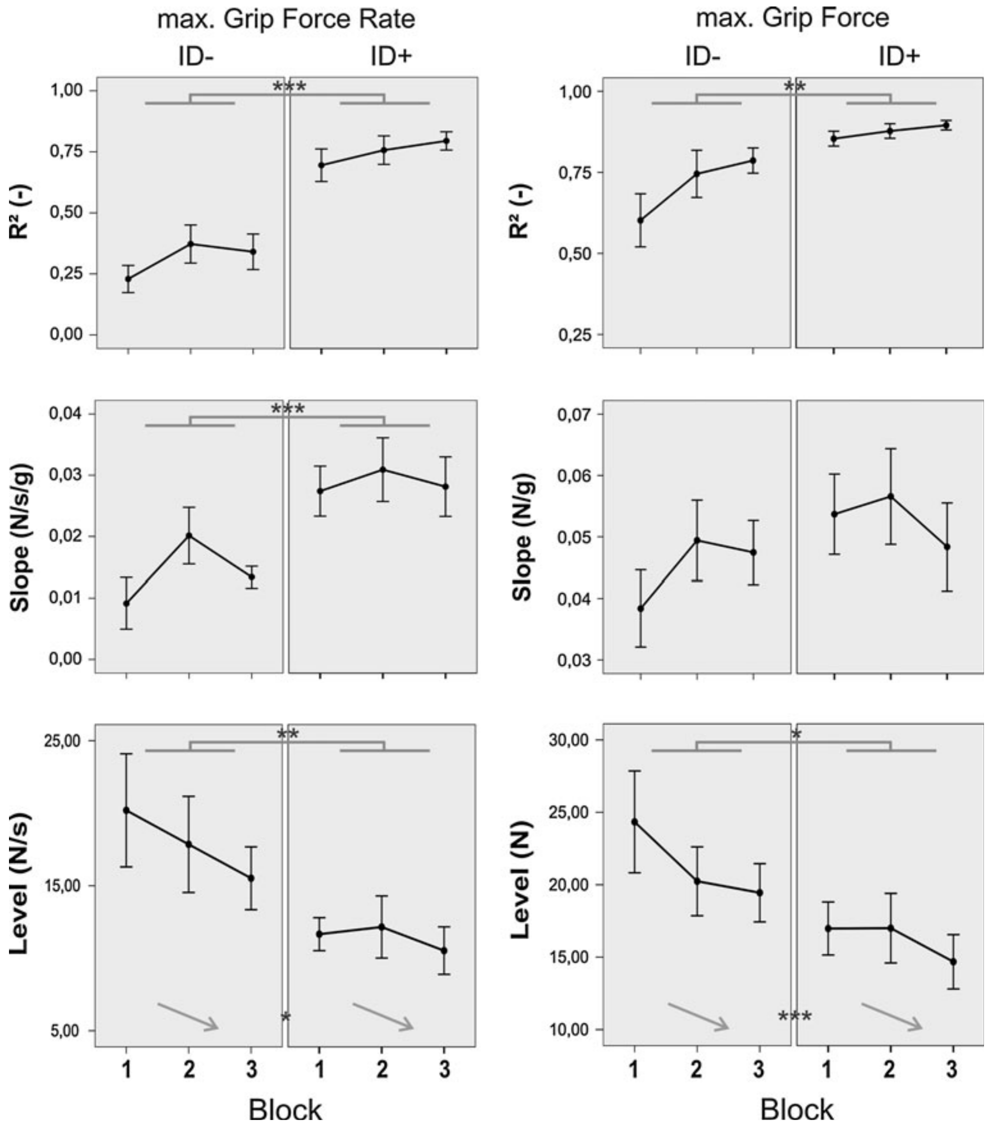

Fig. 5 Results of the linear regression between grip force measures (maximum grip force rate and maximum grip force) and weight calculated for individual performance within blocks. The averages and the standard errors of the coefficient of regression R^2, the slope and the level are shown across the three blocks tested for both conditions ID− and ID+. The *brackets* indicate a significant effect of "condition," the *arrows* a significant effect of "block." ***$P \leq 0.001$, **$P \leq 0.01$, *$P \leq 0.05$

force rate was closer to zero in the ID+ condition (Level-LFRmax "Condition": $F_{1,20} = 15.7$, $P = .003$; mean ID+: −29.0 N/s, ID−: −34.9 N/s), reflecting the fact that the magnitude of the load force rate was on average higher when object identity was not known (see Fig. 4). No other effect reached the level of statistical significance for the maximum load force rate (all other main effects and interactions: $P > .1$). For the liftoff time, only the difference in slope reached the level of significance in both conditions (Slope-Tload "Condition": $F_{1,20} = 5.5$, $P = .041$; mean ID + : 0.177 ms/g, ID−: 0.269 ms/g; see Fig. 4). The liftoff time increased with the weight when object identity was unknown, while this relationship was less obvious in condition ID+. A trend for statistical significance in the interaction (Slope-Tload "Condition × Block": $F_{2,20} = 3.2$, $P = .063$) was due to the fact that the slope decreased across blocks for the ID− condition (ID− Block 1: 0.329, Block 2: 0.309, Block 3: 0.168 ms/g). No other effect approached statistical significance ($P > .1$).

Discussion

Skilled interaction with the environment requires that known properties of the external world are incorporated into the planning of motor actions. The present study shows that grip force production anticipates the physical characteristics of grasped familiar objects already from the first moments following contact. In particular, the objects were well known from daily experience and the necessary grip force had to be inferred from learned associations between object identity and the relevant object characteristics. Two highly effective cues, namely experience with the same object from the preceding lifting trial and object size, were not helpful in the present design. On the one hand, each lift was preceded by lifting of a neutral object and also the second-last object was never equal to the current one so that refinement of short-term sensory motor memory for constant objects was not possible (Johansson and Westling 1988; Witney et al. 2000; Flanagan et al. 2001). On the other hand, due to the presentations of object pairs with similar size but different weight, object size was also not informative as compared with experiments with size–weight congruent objects (Gordon et al. 1991a, b; Cole 2008; Li et al. 2009). Since the objects of everyday life differed in many other factors that cannot easily be controlled (e.g., compliance of the material, necessary grip aperture, and stability of the placement), a control experiment was devised that held this factors constant but prevented the recognition of the objects.

Grip force scaling

The maximum grip force rate best discriminated between the two experimental conditions. When object identity was known, this measure clearly differentiated between the two paired objects with different weight and exhibited a near linear relationship with the object weight. The only exception was a missing effect for the biscuit–spaghetti pair reflected by relatively low grip force rates for the spaghetti pack in the linear regression. This finding corresponded with a frequent comment of the subjects following the experiment, who stated, that the spaghetti package felt surprisingly heavy during lifting. The underlying reason is, however, unclear. Contrary to the condition with known object identity, the grip force rate did not differ between most objects of the pairs, and no linear relationship between grip force rate and object weight was documented when the object could not be recognized. The finding of physically correct grip force rates in two pairs (candle–tea, book–filter) may be attributed to the fact that the lighter of the two paired objects consisted of a less rigid material, which dampens a rapid grip force increase by elasticity. In summary, the maximum grip force rate before liftoff is the most sensitive measure to indicate successful preplanning of manual interaction with familiar objects (Gordon et al. 1991b; Johansson and Westling 1988; Li et al. 2009; Nowak et al. 2007b). If the object identity is unknown and no other cues can be used to estimate object characteristics, the maximum grip force rate varies widely between (see Fig. 3) and within (see low R^2 in Fig. 5) subjects with no clear relationship to object features. Obviously, most subjects did not attempt to scale their grip force rate to the size of the object in the absence of other meaningful information. Possibly, subjects dismissed a strategy of assuming constant density quickly after the negative experience with the first object pair.

The findings for the maximum grip force reflect the capacity of the motor system to rapidly process incoming sensory information to update motor output. In the condition without object knowledge, the maximum grip force was higher for the heavier object in most of the pairs, and the force was linearly scaled to the object weight, while during the force increase phase no such relationship was obvious as revealed by the variable maximum grip force rate. The direct comparison of the regression parameters revealed clearly higher linearity for the maximum grip forces as compared with the earlier grip force rates. It has been repeatedly shown that sensory information signaling of object weight from liftoff is processed rapidly and the motor output is adjusted accordingly (Johansson and Westling 1988; Johansson and Edin 1993; Johansson and Flanagan 2009; Gordon et al. 1991b). Also, when object identity was known, the linearity increased from the occurrence of maximum grip force rate until maximum grip force. This suggests that sensory based corrective mechanisms are active irrespectively from the primary advantage of object knowledge. Although, the increase in linearity was somewhat weaker, the scaling of the maximum grip force to the weight was more precise when the object identity was known. Therefore, rapid adjustments after liftoff when object identity was unknown could not fully compensate for the benefit of prior knowledge.

Particularly for the maximum grip force, the two heaviest objects differed from the linear trend in two different directions. The relatively low grip force for the milk may have been due to a partial saturation of the force in the unnatural three-finger grip for the heavy object. Individual strength may have influenced grip force for the relatively heavy milk, while for the other lighter objects an effect of strength on the grip forces seems unlikely. The sometimes relatively high grip force for the book may in turn have been due to eventual eccentric grasps of the relatively wide book causing torque loads that had to be additionally compensated (Kinoshita et al. 1997).

Apart from deviations for individual subjects and specific objects, the grip force was clearly scaled to known object characteristics, although tactile perception was disturbed by the use of the force sensor arrays and caps covering the fingers. For the grasping phase before liftoff, this reflects the independence of preplanning from somatosensory feedback and emphasizes the feedforward character of this control mode (Miall and Wolpert 1996; Wolpert and Flanagan 2001; Hermsdörfer et al. 2005; Nowak and Hermsdörfer 2003a, b). The fact that the slope and the coefficient of the regression for maximum grip force was clearly superior to the corresponding parameters of the earlier grip force rate, in particular with unknown objects, proves successful processing of sensory information despite tactile disturbances. After liftoff, shear forces are probably quite precisely transferred through the plastic and rubber layers with high friction surfaces, so that weight can be detected by skin receptors. In addition, proprioceptive afferents from finger, hand muscles and tendons can compensate for loss of cutaneous information (Häger-Ross and Johansson 1996).

In the unwrapped condition, the objects differed also in friction between fingers and surface material. However, the relatively good prediction of grip force rate from the objects' weight suggests that friction did not play a primary role. Apart from the facts that none of the materials had an extreme friction (see Buchholz et al. 1988) and the high friction of the rubber caps provided a relatively safe contact between fingers and object (Kinoshita 1999), subjects may not have extensively used cues about friction due to the degraded tactile information. Nevertheless, it is conceivable that in other situations of lifting everyday objects, knowledge about surface friction is used as a valid cue for the scaling of grip forces. While the measurement of grip forces using sensor arrays at the finger tips enables the present analysis of the interaction with object of everyday life, it can be very critical in studies with an important role of processing tactile information.

Load forces

Different from the maximum grip force rate, the maximum load force rate was near linearly related to the object weight even when object identity was unknown to the subjects. This difference probably originates from the fact that load forces are limited by the object's weight, while grip forces can be arbitrarily high as long as the object's material provides resistance. Thus, a very light object may lift off quickly and a low load force rate may be registered even if the weight was not anticipated. Notably, previous studies of motor anticipation during grasping and lifting of objects of everyday life were based on the registration and analysis of load forces (Gordon et al. 1993; Duff and Gordon 2003; Dawson et al. 2010). The present findings can be critical for the interpretations of those and future studies basing solely on load force measurement. However, the demonstrated effect may be particularly strong when a wide range of objects weights, including very light weights, is used as in the present study. In addition, successful anticipation is still obvious from lower interindividual variability and a higher regression coefficient for the maximum load force rate when the object identity was known. Finally, a closer inspection of the load force rate profiles, as provided by Gordon and colleagues (Gordon et al. 1993), can reveal whether a load force production anticipates a weight (symmetric profile) or is interrupted due to unexpected liftoff (asymmetric profile). Nevertheless, the present data suggest that grip force is the more suitable measure to distinguish between successful and absent or degraded anticipation of object properties in grasping and lifting studies.

Trend to isochrony

Isochrony refers to the finding of identical durations of force increases, independently of the final force level in experimental tasks of isometric force production (Freund and Büdingen 1978; Gordon and Ghez 1987). In the present natural task, isochrony was not reached. Nevertheless, the slope of the regression for the relationship between the time interval from grip force onset until object liftoff (liftoff time) and object weight was flatter for the condition when object identity was known as compared with the control condition. Thus, successful grip and load force scaling resulted in less distributed liftoff times for different objects indicating a trend for isochrony. The finding of a flatter slope in the familiar condition also restricts the value of the liftoff time as a measure for the precision of anticipation during weight lifting.

Optimization

The central finding of successful anticipation during the first lift of familiar objects leads to the question whether force production is optimized during another interaction with the same object in the same experiment. However, such an optimization was weak. Although, the regression parameters for the grip force rate and grip force indicated a slight improvement across blocks, this effect did not reach statistical significance. It seems unlikely that this is due to a ceiling effect, since the coefficients of regression are not very close to the ideal "1" (Fig. 5), meaning that there is still room for further improvement. Therefore, in our experiment, information about relevant object properties acquired during single lifts of objects of everyday life was not used to update the corresponding representation or internal model of the object. The most feasible explanation seems that the amount of practice with different objects before the same object is encountered again and was too high to allow for consolidation of this information. In addition, there may be no strong drive for optimization when familiarity with the object is very high, and its salience is low. It may be of relevance that the numerical increase in linearity for the scaling of grip force maximum was relatively strong (though not significant) when object identity was unknown, although the available cues were weak for the wrapped objects. This suggests that familiarity may be critical. In the case of novel objects, available somatosensory information from previous lifts and visual cues is integrated to improve the internal model (Gordon et al. 1991a, b; Flanagan and Johansson 2009; Nowak et al.

2007a; Li et al. 2009). It has to be noted that the present experiment was limited to three blocks, and a slow improvement during continuing lifting seems feasible. In addition, we cannot exclude that diminished tactile input from the fingertips due to the force sensors deteriorated the optimization.

Interestingly, the grip force level decreased across the blocks irrespectively from the condition. The most plausible reason is a generalized increase in confidence with the task, leading to a decrease in the safety margin that provides security against slippage (Johansson and Westling 1984; Westling and Johansson 1984; Hermsdörfer et al. 1999, 2004). In line with this reasoning, the grip force level was higher for the control compared with the normal viewing condition, suggesting that a high safety margin was selected when objects properties are unknown. Independency of the grip force level from other aspects of force control during object manipulation has been demonstrated in healthy as well as in pathological conditions (Hermsdörfer et al. 2003, 2004; Nowak et al. 2001).

Conclusion

In conclusion, the study confirms a highly elaborated mechanism to predict the weight of familiar objects and to implement this information into the generation of grip forces when interacting with objects. Weight is probably the most dominant factor as obvious by near linear grip force–weight scaling already at very early phases during a lifting action. However, other object-specific factors additionally influence force production. The internal model of the object is not substantially updated and optimized during variable practice; rather, sensory mechanisms are always at work to further adjust grip force as soon as relevant sensory information is available.

Acknowledgments The study was supported by grants from the German Federal Ministry of Education and Research (BMBF, project 01GW0572) and from the German Research Foundation (DFG, HE 3592/6). We thank Nathalie Gales for skillful editing of the manuscript.

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Veröffentlichung II

Neuropsychologia 61 (2014) 222 234

Contents lists available at ScienceDirect

Neuropsychologia

journal homepage: www.elsevier.com/locate/neuropsychologia

The impact of unilateral brain damage on anticipatory grip force scaling when lifting everyday objects

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ARTICLE INFO

Article history:
Received 9 November 2013
Received in revised form
13 June 2014
Accepted 20 June 2014
Available online 28 June 2014

Keywords:
Hemisphere differences
Sensorimotor control
Grasping and lifting
Anticipation
Grip force
Internal model
Apraxia
Tool use

ABSTRACT

The scaling of our finger forces according to the properties of manipulated objects is an elementary prerequisite of skilled motor behavior. Lesions of the motor-dominant left brain may impair several aspects of motor planning. For example, limb-apraxia, a tool-use disorder after left brain damage is thought to be caused by deficient recall or integration of tool-use knowledge into an action plan. The aim of the present study was to investigate whether left brain damage affects anticipatory force scaling when lifting everyday objects. We examined 26 stroke patients with unilateral brain damage (16 with left brain damage, ten with right brain damage) and 21 healthy control subjects. Limb apraxia was assessed by testing pantomime of familiar tool-use and imitation of meaningless hand postures.

Participants grasped and lifted twelve randomly presented everyday objects. Grip force was measured with help of sensors fixed on thumb, index and middle-finger. The maximum rate of grip force was determined to quantify the precision of anticipation of object properties.

Regression analysis yielded clear deficits of anticipation in the group of patients with left brain damage, while the comparison of patient with right brain damage with their respective control group did not reveal comparable deficits. Lesion-analyses indicate that brain structures typically associated with a tool-use network in the left hemisphere play an essential role for anticipatory grip force scaling, especially the left inferior frontal gyrus (IFG) and the premotor cortex (PMC). Furthermore, significant correlations of impaired anticipation with limb apraxia scores suggest shared representations. However, the presence of dissociations, implicates also independent processes.

Overall, our findings suggest that the left hemisphere is engaged in anticipatory grip force scaling for lifting everyday objects. The underlying neural substrate is not restricted to a single region or stream; instead it may rely on the intact functioning of a left hemisphere network that may overlap with the left hemisphere dominant tool-use network.

1. Introduction

Skilled and stable lifts of everyday objects depend on our ability to anticipate the physical properties of the objects we are interacting with. Every day we lift hundreds of objects with great dexterity in a highly automated way. The execution would be slow and clumsy if the motor system had to rely entirely on sensory input and feedback mechanism (Flanagan & Johansson, 2009). Anticipatory feedforward mechanisms are employed to adjust adequate grip forces in the early stage of a grasping and lifting movement.

A number of studies demonstrate that force scaling is based on different characteristics of the object. Important characteristics include object weight, size, shape, surface properties, weight distribution and identity, as well as immediate sensorimotor memory obtained from previous lifts with the same object (Cadoret & Smith, 1996; Cole, 2008; Cole & Rotella, 2002; Flanagan & Beltzner, 2000; Flanagan, Bittner, & Johansson, 2008; Gordon, Westling, Cole, & Johansson, 1993; Hermsdörfer, Li, Randerath, Goldenberg, & Eidenmüller, 2011; Jenmalm & Johansson, 1997; Johansson & Westling, 1984; Salimi, Hollender, Frazier, & Gordon, 2000). One of the most important cues when lifting objects is size, which enables an estimation of an object´s weight if the material is known, even before the grasped object lifts off. Grip and load force measures

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http://dx.doi.org/10.1016/j.neuropsychologia.2014.06.026
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reflect this anticipation of object-weight derived from size information (Cole, 2008; Flanagan & Beltzner, 2000; Gordon, Forssberg, Johansson, & Westling, 1991a, 1991b; Li et al., 2009; Li, Randerath, Goldenberg, & Hermsdörfer, 2011).

However, in daily routine, size cues are not sufficient for dexterous and stable grasping. There are small but heavy objects as well as large lightweight objects. Nevertheless, in daily routines we usually successfully adjust our grip force to an object's actual weight. Moreover, we anticipate the object's weight before any direct sensory information is available (Gordon et al., 1993; Hermsdörfer et al., 2011; Johansson & Westling, 1988). In one of our previous studies (Hermsdörfer et al., 2011) healthy subjects lifted twelve different objects of everyday life that consisted of object pairs with similar size but different weight to make size information irrelevant. For example, the set of items to be lifted contained a heavy book as well as an equally sized package of light coffee filters. For both types of objects, subjects scaled the maximum grip force rate according to the physical weight before lift-off, suggesting that weight information was successfully predicted from knowledge of object identity. Thus, memory representations associating object identity with relevant object characteristics enable us, to specify the grip force when lifting commonly used objects (Gordon et al., 1993; Hermsdörfer et al., 2011). Therefore, in daily routine objects weight and other relevant object properties are anticipated precisely in the moment of grasping, before any feedback is available. Anticipatory grip force scaling helps us to quickly establish an adequate grip force that prevents slippage of the object on the one hand, on the other hand it avoids exaggerated forces, preventing e.g. damage of fragile objects.

The neural substrates which enable precise anticipation when lifting everyday objects are not yet determined. Important sources of information are investigations in patients with localized brain damage during object lifting.

Patients with cerebellar degeneration and control subjects similarly produced grip forces scaled to the size of the object when a large and a small object were lifted for the first time (Rabe et al., 2009). Thus, the cerebellum seems not to be critically involved in the anticipatory scaling of grip force to object properties. Furthermore, preserved force scaling according to object size is reported in patients with Parkinson's disease (Ingvarsson, Gordon, & Forssberg, 1997), but there is a dissenting report in a single case with basal ganglia stroke (Dubrowski, Roy, Black, & Carnahan, 2005). In patients with cerebral palsy, impaired force scaling for the involved hand is observed (Gordon & Duff, 1999). However, deteriorating influences of paresis can usually not be excluded in these patients. When patients with cortical lesions due to stroke used their non-paretic ipsilesional hand to lift boxes of different sizes, they typically anticipated object size in the same way as healthy control subjects did irrespectively of the side of the lesion (Li et al., 2011). Few exceptions are however reported following damage to the left posterior hemisphere (Li, Randerath, Goldenberg, & Hermsdörfer, 2007; Li et al., 2011).

Evidence from neuroimaging is scarce. The findings of one fMRI-study (Chouinard, Large, Chang, & Goodale, 2009) investigating grasping and lifting with the right hand, suggest that different regions compute for different object properties. Size is computed by the left postcentral area (S1), the left anterior intraparietal area (AIP), the left superior parietal lobule (SPL) and bilateral fusiform gyri (Fus). The weight for objects recruits left central sulcus (M1), Density judgments based on perceived heaviness are predominantly coded by left ventral premotor area (PMv). The authors propose that for judgments about density the PMv integrates sensory information about the size and weight of objects.

Repetitive transcranial magnetic stimulation (rTMS) of the dorsal premotor cortex (Chouinard, Leonard, & Paus, 2005) has been shown to disrupt force scaling on the basis of arbitrary color cues associated with object weight. Findings of regions responsible for force scaling according to the experience from the previous lift are controversial.

Chouinard et al. (2005) found impaired force scaling after repetitive transcranial stimulation (rTMS) of the primary motor cortex (M1) (Chouinard et al., 2005), whereas rTMS of the ventral premotor cortex (PMv) also resulted in impaired force scaling according to the previous lift (Dafotakis, Sparing, Eickhoff, Fink, & Nowak, 2008).

While most clinical studies have concentrated on the role of size information for force scaling, only few have analyzed the processing of other object information such as object-identity when lifting everyday objects (Dawson, Buxbaum, & Duff, 2010; Duff & Gordon, 2003).

Lifting everyday objects underlies specific demands. For an optimal task performance stored knowledge about specific object characteristics from previous experiences must be retrieved.

The manipulation of objects of daily life is particularly interesting in relation to the phenomenon of limb apraxia. Limb apraxia is defined as a neuropsychological syndrome that disturbs skilled motor actions also in the absence of any primary motor or sensory disorders (Buxbaum, Kyle, Grossman, & Coslett, 2007; De Renzi, Faglioni, Lodesani, & Vecchi, 1983; Frey, 2007; Geschwind, 1975; Heilman, Rothi, & Valenstein, 1982; Kimura, 1982; Liepmann, 1908; Morlaas, 1928; Rizzolatti & Matelli, 2003; Sirigu et al., 1995). According to the concept of apraxia suggested by Goldenberg (2009) the syndrome affects three domains of actions: the imitation of meaningless gestures, the performance of meaningful gestures (like communicative gestures or pantomime of tool-use) and use of tools and objects (Goldenberg, 2009). Behavioral studies in affected patients as well as lesion studies provide evidence that the imitation of meaningless gestures and the pantomime of tool use are two independent sequels of left brain damage, since they can occur independently in individual patients (Bartolo, Cubelli, Della Sala, Drei, & Marchetti, 2001; Goldenberg & Hagmann, 1997; Tessari, Canessa, Ukmar, & Rumiati, 2007) and have different cortical representations (Goldenberg, Hermsdörfer, Glindemann, Rorden, & Karnath, 2007; Goldenberg & Karnath, 2006). Nevertheless these deficits frequently co-occur after left brain damage and are considered variants of apraxia (Buxbaum, 2001; Rothi, Ochipa & Heilman, 1997). There are different concepts about whether pantomime of tool use and actual execution of the action base on one common motor representation (Buxbaum et al., 2007; Rothi et al., 1997) or both modes of action are realized by different cognitive mechanisms (Goldenberg et al., 2007; Osiurak, Jarry, & Le Gall, 2011). Independent of the proposed underlying cognitive process apraxia is typically most severe during the pantomime of tool-use and the symptoms decrease when the patients are allowed to actually manipulate the object (Buxbaum, Giovannetti, & Libon, 2000; Clark et al., 1994; Goldenberg, Hentze, & Hermsdörfer, 2004; Liepmann, 1908; Wada et al., 1999). However, even though significant improvement is shown, movement content errors and irregularities in movement kinematics still occur for the use of daily life objects (Hermsdörfer, Li, Randerath, Goldenberg, & Johannsen, 2012; Randerath, Goldenberg, Spijkers, Li, & Hermsdörfer, 2011; Sunderland, Wilkins, & Dineen, 2011).

A recent study in apraxic patients revealed, that there are dissociable mechanisms involved in grasping versus using tools. Patients with impaired tool-use have lesions predominantly in the supramarginal gyrus, whereas erroneous grasping is more strongly associated with lesions in the inferior frontal gyrus and angular gyrus (Randerath, Goldenberg, Spijkers, Li, & Hermsdörfer, 2010). From errors during tasks involving manipulation it has been proposed that apraxia is partly related to deficient internal models for planning object related actions, compared to relatively intact on-line, feedback driven control of action (Buxbaum, Johnson-Frey,

& Bartlett-Williams, 2005; Haaland, Harrington, & Knight, 1999). These considerations suggest a relationship between apraxia and anticipatory skills while lifting everyday objects.

A recent study that investigated load force production in six patients with left-sided stroke during lifting everyday objects is considered as support for the notion of deficient feed-forward planning in apraxia (Dawson et al., 2010). Two patients with apraxia showed weak or absent anticipation of object weight. The two patients had lesions in the inferior parietal lobe and in the superior and middle temporal lobes. The authors propose that an object specific memory in the ventro-dorsal stream may be involved in the long-term storage of internal models. The question remained open, whether impaired force scaling when lifting everyday objects can also be shown in a larger patient sample and for grip force measures, which have been shown to be superior to load force measures in a comparable paradigm (see Hermsdörfer et al., 2011). Alternatively to the proposed relationship with limb apraxia, it is possible that anticipatory skills in object manipulation may reside in the motor-dominant left hemisphere with a non-casual-relationship with apraxia due to the same hemispheric dominance. Furthermore, it could be proposed that object properties relevant for manipulation are processed in an anatomically distributed organization without crucial involvement of specific cortical areas. Kinematic studies of tool-use actions support the notion that deficits of motor skill and apraxic action errors may be independent consequences of left-brain damage (Hermsdörfer, Hentze, & Goldenberg, 2006; Hermsdörfer, Li, Randerath, Roby-Brami, & Goldenberg, 2013). Similarly, a series of recent studies, that did not primarily address apraxia, reported hemisphere-specific deficits during the executions of various goal-directed movement tasks in unilateral brain damaged patients (Schaefer, Haaland, & Sainburg, 2007, 2009).

To explore the different possibilities we examined the lifting of everyday objects in 16 stroke patients with unilateral left brain damage (LBD). Importantly to rule out general influencing factors such as the mere presence of stroke or specific deficits following right brain damage ten stroke patients with unilateral right brain damage (RBD) as well as twenty-one age-matched healthy controls were tested. Stroke patients executed all tasks with their non-paretic ipsi-lesional hand. Different from previous studies that were restricted to measuring the load forces with scales when everyday objects were lifted we also registered grip forces, since one of our former studies in healthy subjects revealed, that in the present paradigm grip force is a more reliable signal than load force (Hermsdörfer et al., 2011).

Based on the previous findings on the importance of left hemisphere for skilled hand-object interaction and tool-use we hypothesize, that left brain damage affects anticipatory force production for lifting everyday objects. We assume that patients after RBD might perform normal. To analyze whether any deficit of anticipatory grip force scaling in patients with left brain damage may be associated with apraxia, we assessed pantomime of tool-use and imitation of hand and finger postures.

Furthermore, by accomplishing lesion analyses we aimed at identifying critical lesion-sites associated with impaired force scaling when lifting everyday objects.

2. Material and methods

2.1. Participants

Twenty-six stroke patients were investigated. Patients with a single unilateral cerebrovascular accident and with no evidence of bilateral lesions at MRI or CT examinations were included. In 16 patients the stroke had affected the left hemisphere (LBD group), 10 patients suffered from a right hemispherical stroke (RBD group). All of the patients were tested with their ipsilesional hand. The LBD group consisted of 9 females and 7 males. Their mean age was 55.6 years (range 29–71). The RBD group comprised 1 female and 9 male with the mean age of 57.1 years (range 37–74). All subjects were pre-morbidly right-handed as verified by a handedness questionnaire (Salmaso & Longoni, 1985). Mean time post stroke onset was 3.0 months (range 1–14). The medical report provided further information: 15 patients were aphasic, 16 patients were hemiparetic on the contralesional side and 8 RBD patients suffered from a hemianopia or hemineglect towards the left side. The individual etiologies as well as clinical and demographic data of the patients are summarized in Table 1. The affected brain structures were localized with current radiographic data available at the time of data analysis.

Twelve control participants had to execute the tasks with their left hand (CL group) and 9 healthy controls used their right hand (CR group). All control participants were right-handed. In the CL group half of the participants were male; the mean age was 55.1 years (range 29–73). In the CR group 6 subjects were male; the mean age was 57.2 years (range 35–73).

The study design was approved by the ethical committee of the Medical Faculty of the Technische Universität München. All subjects gave their informed consent for participation in the study, which was performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

2.2. General task

The general task was to lift twelve objects of everyday life. Subjects sat at a table, with the grasping hand resting comfortably on the table approximately 20 cm right from the body-midline. A scale with a platform (diameter 25 cm, 5 cm above the table top) was placed in a comfortable reaching distance (about 50% of maximal reaching distance) in front of the body. The instruction was to reach for the object, to grasp it with the thumb, the index and middle finger in opposition (three finger grip), and lift it about 5 cm above the platform. Subjects were told to make a rather fast but not abrupt lifting movement to avoid probing strategies. Care was taken that they kept this movement strategy throughout the test. To avoid any cue about object weight from the observation of the examiner´s movement, subjects were requested to close their eyes during the placement of the objects. Then a pause of 5 s enabled careful visual inspection of the object. Following a vocal pre-warning a tone indicated the start of the grasping movement. A second tone 3.5 s later indicated the placement of the object back onto the scale.

2.3. Objects

12 real everyday objects were chosen based on familiarity with respect to identity and manipulation, and all objects enabled comfortable grasping. The objects included pack of cigarettes, tissues, tea package, coffee filter, mug with a tooth brush, biscuit, liquor, cup, candle, carton with spaghetti, book, and milk carton. The selected objects covered a wide range of weights between 26 g (cigarette pack) and 1060 g (milk carton) (see Fig. 1A). The selection criteria for the everyday objects guaranteed easy identification from the visual appearance. When presented to the participants, the objects were placed with their longer axis oriented in the vertical direction. To enable a comfortable grasp objects were slightly rotated. The objects that contained food or goods were new and unopened. This was obvious from the visual appearance and subjects were also informed about this fact. The plastic cup and the porcelain mug were empty; subjects were able to verify this from their viewing position. All participants lifted a neutral, gray plastic cylinder (diameter 75 mm, height 80 mm, weight 400 g) during the first six trials to get familiar with the task. Furthermore, the neutral object was lifted between lifting-trials of everyday objects to neutralize potential carry-over effects from lifting of the last familiar object on to the current object (sensorimotor memory) (see Johansson & Westling, 1984, 1988). Evaluation of the training trials revealed the typical decrease of the grip force to an approximately constant force level during the first four lifts. The lifts of the neutral object were not further considered in the statistical analysis.

2.4. Procedure

The twelve everyday objects were lifted in succession interrupted by lifts of the neutral object. After completion of a block of all twelve objects a second and a third block followed (blocks 1, 2, 3). Objects were presented in a fixed randomized order, which differed in each block. Regular breaks of about 10 s were introduced after each lifting movement. When interviewed after the session, all subjects (patients and controls) commented to be highly familiar with each of the twelve everyday objects. If aphasic patients were unable to comment, we asked them, to select each single object out of the complete set ("Can you show me the package of biscuits"). All patients pointed fluently to the correct object.

2.5. Data recording

The grip force was measured using force sensor arrays applied to the pads of the distal phalanxes of the three grasping fingers. Each sensor array measured

Table 1
Demographic and clinical information for all participants, including results from hand- and finger imitation and pantomime of tool-use test.

Name	Age	MOS	Lesion				Sex	Aphasia	Paresis	Neglect/ anopsie	Anticipation	Imitation		Pantomime
			Ischemia/ bleeding	Side	Size (cc)	Locus						Hand	Finger	
AB10	38	1	b (ICB)	LBD	19.1	t, f, o, i	f	0	0	0	0	0 (20)	0 (20)	0 (55)
BR03	40	3	i (MCA)	LBD	354.1	t, f, o, p, pc, prec, i, precu, cu,bg, ro, hi, ca, fus	m	1	1	0	0	0 (18)	0 (20)	1 (39)
HM22	66	3	i (MCA)	LBD	175	t, f, o, p, prec, pc, i, bg, hi, ca, ro	f	1	1	0	0	0 (18)	0 (19)	1 (28)
HS22	37	1	b (ICB)	LBD	26.8	t, f, prec, i, bg, hi	m	1	1	0	0	0 (19)	0 (20)	1 (44)
HS24	66	1	i (ACA, MCA)	LBD	14.2	f, prec, bg, ro, i	f	1	0	0	0	0 (18)	1 (15)	1 (44)
KG25	71	14	i (MCA)	LBD	116.2	t, f, o, p, i, pc, ro, bg, hi	m	1	1	0	0	0 (18)	n.m.	1 (35)
SI06	60	11	b (ICB)	LBD	32.8	t, bg, i, hi	f	1	1	0	0	0 (19)	1 (13)	1 (27)
SX05	54	1	i (MCA)	LBD	14.4	bg, i	m	1	1	0	0	0 (20)	0 (17)	0 (54)
ZI14	63	2	b (ICB)	LBD	43	t, f, fus, i, hi	f	1	1	0	0	0 (18)	1 (14)	0 (50)
BM11	29	2	svt	LBD			f	1	0	0	1	0 (19)	0 (20)	0 (48)
HM21	69	2	i (ACA, MCA)	LBD	236.9	t, f, pc, prec, i, SMA, ci, bg, ro, ci, hi	f	1	1	0	1	1 (13)	1 (10)	1 (05)
KL23	65	2	i (MCA)	LBD	25.1	t, f, o, p, pc, prec, i, ro	m	1	0	0	1	1 (13)	1 (16)	0 (46)
MJ19	70	2	b (ICB)	LBD	25.5	o, p, pc	m	1	0	0	1	1 (14)	0 (18)	0 (51)
MP02	47	4	i,b (MCA, PCA)	LBD	230.6	f, p, pc, prec, precu, cu, ro, i, SMA, ci, ca, li	f	1	0	0	1	1 (13)	1 (03)	1 (05)
NJ24	64	8	i (MCA)	LBD	149.1	t, f, I, ro, pc, prec, bg, hi	m	1	0	0	1	0 (18)	1 (16)	1 (42)
SF07	50	1	i (MCA)	LBD	85.8	t, o, p, prec, hi, fus, ca, ci, cu, ro	f	1	1	0	1	0 (20)	0 (20)	1 (43)
mean LBD	55,56	3,62			103.24							17,35	16,5	43,29
GF17	58	2	b (ICB)	RBD	83.7	t, p, o, fus, ro, i, ca, hi, cu, precu	m	0	1	1	0	1 (17)	1 (13)	0 (53)
HS08	68	4	i (MCA)	RBD	171	t, p, prec, pc, i, ro, bg	m	0	1	1	0	1 (16)	0 (18)	0 (52)
HT20	65	1	i (MCA)	RBD	41.4	t, f, bg, i, ro	m	0	1	1	0	0 (20)	1 (16)	0 (48)
KR20	37	1	i (MCA)	RBD	75	f, p, i, ro, prec, bg, pc	m	0	1	1	0	0 (18)	0 (20)	0 (55)
KS13	51	1	i (MCA)	RBD	101.5	t, f, p, I, ro, pc, prec, bg	m	0	1	1	0	0 (18)	1 (16)	0 (51)
KW23	74	2	b (ICB)	RBD	28.3	t, p, fus	m	0	0	1	0	1 (13)	1 (11)	0 (49)
SH26	67	1	i (MCA)	RBD	97	t, f, o, p, bg, hi, ro	f	0	1	1	0	1 (11)	1 (11)	0 (48)
DB09	54	2	i (MCA)	RBD	80.6	t, f, p, prec, pc, i, ro, bg	m	0	0	1	1	0 (20)	0 (17)	0 (55)
MM04	42	4	i (PCA)	RBD	8.7	ca, li, hi, fus	m	0	0	0	1	0 (20)	0 (19)	0 (54)
UL01	55	3	i (ACA, MCA)	RBD	108.1	t, f, p, i, prec, bg, ro, SMA, ci	m	0	1	0	1	1 (16)	0 (17)	0 (49)
mean RBD	57.8	2.27			76.36							17.8	17.11	51.1

MSO: months since onset of stroke. Ischemia/bleeding: i=ischemia; b=bleeding, ICB=intra-cerebral bleeding; MCA=middle cerebral artery; ACA=anterior cerebral artery; PCA=posterior cerebral artery; svt=sinus venous thrombosis. Lesion-side: LBD=left brain damage; RBD=right brain damage. Lesion-size: cc=cubic centimeter. Lesion-location: t=temporal; f=frontal; o=occipital; p=parietal; pc=postcentral; prec=precentral; i=insula; SMA=Supplementary Motor Area; ci=cingulum; cer=cerebellum; bg=basal ganglia; precu=precuneus; cu=cuneus; ro=rolandic operculum; hi=hippocampus; fus=fusiform; ca=calcerine; li=lingual. Sex: m=male, f=female. Aphasia: tested with Aachen Aphasia test (Huber, Poeck, Weniger, & Willmes, 1983). Pantomime and imitation: tests of G. Goldenberg (see also Goldenberg & Hagmann, 1997; Goldenberg et al., 2003; Goldenberg et al., 2007). Data: 1=impairment, 0=no impairment; (score/ max. test-score).

20 × 20 mm and contained 16 force sensors (sensor S2001, Pliance System, Novel, Munich, Germany). The thin (0.5 mm) and flexible arrays were fixed to the finger pads by rubber caps cut from standard medical gloves (see Fig. 1B). The cables were fixed loosely to the palmar fingers and hand with tape. The calibrated pressure range of the arrays ranged from 500 to 2000 hPa, corresponding to 0.5 to 20 N/cm². The sensors were zero-calibrated in the mounted position. Bending of the sensors and hysteresis could cause absolute errors of 10%. With no change of mounting within one session the relative errors were however smaller. With this configuration, grip forces could be measured during grasping arbitrary objects, however, at the expense of absent direct skin contact with the object. A preceding study in healthy subjects (Hermsdörfer et al., 2011) showed that the sensors and rubber caps did not impede anticipatory force scaling. For each sensor array the total force

Fig. 1. (A) Everyday objects lifted in the experiment. (B) Measurement of grip forces. Flexible force-sensors arrays were applied over the pads of the thumb, the index and the middle finger and secured by rubber caps.

was obtained by averaging across the 16 force sensors. Finally the three finger forces were summed up to provide a measure of the instantaneous grip force. Note that this sum of the forces from both sides of the grasped objects is twice of value resulting from normal one-sensor measurements.

The platform from which the objects were lifted was equipped with a force sensor that measured the weight force produced by the objects (accuracy $\pm$ 0.1 N, sampling rate 100 HZ). Producing a load force in the upward direction decreases the sensor reading until the object lifts off. The scale did not provide load information after liftoff.

2.6. Data analysis

All signals from scale and grip force sensors were collected and analyzed with customized software (Hermsdörfer, Hagl, Nowak, & Marquardt, 2003). Specific time points of interest were determined for each lifting trial based on the time courses of grip force and load force. First, the moment of contact between the fingers and the object (TGFonset) was defined as the moment when the grip force exceeded baseline variability ($>$ 0.1 N). Second, after liftoff the maximum grip force (GFmax) and the corresponding time point (TGFmax) were determined. When on rare occasion the grip force continued to increase after the lifting had terminated, the maximum closer to the lifting movement was considered. Between TGFonset and TGFmax the grip force rate (GFRmax) was determined as a local maximum in the first derivative of the grip force profile. The time derivatives were obtained by means of kernel estimates (cut-off frequency 12 Hz (Marquardt & Mai, 1994). If more than one grip force rate peak occurred in the time interval, the first clear peak was considered to represent the prediction of objects properties, while further peaks represent corrective actions (see Johannsson & Westling, 1988). Consequently the first peak was used for the analysis. The criteria were a corresponding grip force of at least 1 N and a minimum decrease of the grip force rate by at least 25% of the peak value following the peak.

From the load force profile the time of lift-off (TLFoffset) was determined as the time point just before the scale reading was zero ($<$ 0.1 N). The interval between TLFoffset and TGFonset was defined as loading time (TLIFT-off). Since a previous study in healthy subjects indicated that load force signals can be problematic (Hermsdörfer et al., 2011), especially with light objects, we did not further analyze load forces in this study.

2.7. Apraxia tests

Severity of apraxia was assessed with two different tests. For testing pantomime of tool-use, the examiner named the action and showed a picture from one out of 20 different tools to the subjects (Goldenberg, Hartmann, & Schlott, 2003; Goldenberg et al., 2007). The task for the patients was to mime the action as if they were holding the tool in hand. Credit points were given for correct hand positions and movements. Pantomime was considered as defective when the score was below the fifth percentile of a control group (45/55) (Goldenberg et al., 2007). In addition to pantomime, the imitation of meaningless hand gestures has been established as a sensitive test of apraxia. Two variants of meaningless gestures were examined (imitation of hand and finger postures). Imitation was classified as disturbed for scores below the fifth percentile of the control group (18 of 20 for hand, 17 of 20 for fingers). For further information see (Goldenberg & Hagmann, 1997; Goldenberg et al., 2007; Goldenberg, Munsinger & Karnath, 2009).

2.8. Lesion analysis

Current MRI scans were available for most of the patients (LBD 15/16, RBD 10/10, see Table 1). Mapping of lesions was carried out by one experimenter without knowledge of test results and clinical features of the patient (for similar procedures and interrater-reliability see also Randerath et al., 2010). Lesions were drawn manually on a T1-weighted standard template with 8 mm slice thickness. The template was based on the 'ch2'-MRI-scan distributed with the MRIcro software (Rorden & Brett 2000; http://www.sph.sc.edu/comd/rorden/), a T1-weighted MRI scan from the Montreal Neurological Institute (http://www.bic.mni.mcgill.ca/cgi/icbm_view). Lesions were mapped onto the slices that correspond to z coordinates -40, -32, -24, -16, -8, 0, 8, 16, 24, 32, 40, and 50 mm in Talairach coordinates by using the identical or the closest matching transversal slices of each individual.

Fig. 2 displays the resulting overlay plots of lesion density in patients with left and right brain damage. In both, left and right brain damaged patient groups the superimpositions show regions typically affected by a middle cerebral artery stroke. Most frequently impaired regions include the inferior frontal gyrus, the insula, and the precentral gyrus as well as adjacent white matter regions. In addition, more posterior areas such as the inferior parietal lobe and the superior temporal lobe were frequently affected.

To identify the structures which are commonly damaged in patients with defective anticipatory force scaling we subtracted the superimposed lesions of patients performing within the control range from those performing below the cutoff score. The scores were derived from linear regression analysis (see Section 2.9). We used proportional values for the MRIcro subtraction analysis, which consequently yielded a percentage overlay plot, see also Rordon and Karnath (2004). This analysis was only performed in LBD patients.

2.9. Statistical analysis

The maximum grip force rate (GFRmax) is widely recognized as measures of anticipatory force scaling because it occurs prior to or at the time of lift-off, well before cutaneous or proprioceptive information from the grasping fingers is available to trigger reactive force corrections (Flanagan & Beltzner, 2000; Johansson & Westling, 1984, 1988; Nowak et al., 2007). Therefore our analysis concentrated on GFRmax. In addition, maximum grip force (GFmax) and the time to lift-off (TLIFToff) were analyzed. In a first step of the statistical analysis we calculated the linear regression between the grip force parameters (GFRmax and GFmax) and the object's weight for every single subject and block. Three objects were excluded in this analysis. It was due to deviations from linearity for the spaghetti and milk item found in a recent study using the same object set in healthy subjects (Hermsdörfer et al., 2011). For the tea package we could not

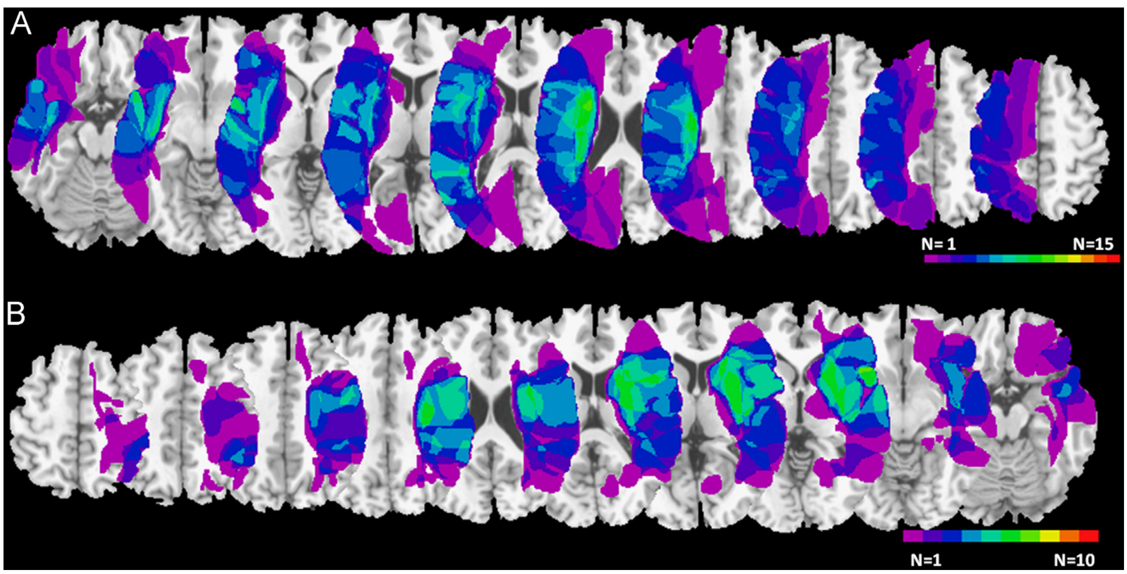

Fig. 2. Lesion locations based on tracing lesions from MRI or CT scans were superimposed on axial slices, separately for 15 LBD (A) and 10 RBD (B) patients. Colors of shaded regions denote the number of LBD and RBD patients with lesion in the corresponding area. *Note*: image of 1 LBD was not available due to missing scans. (For association of the time series to the objects indicated in the figure, the reader is referred to the web version of this article.)

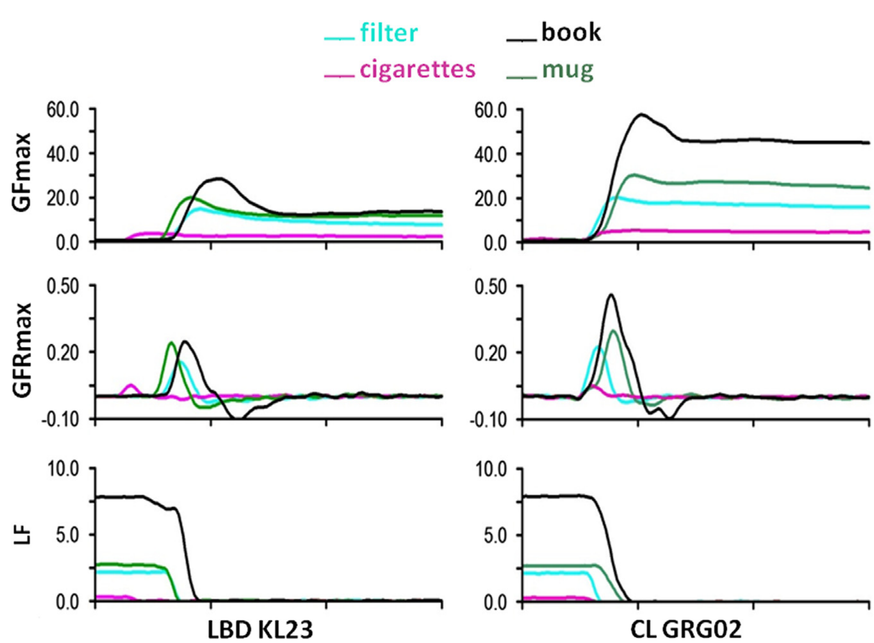

Fig. 3. Time course of the grip force (GF), grip forcer rate (GFR), load force (LF) during the first lift of 4 selected objects (cigarettes, filters, mug, books). Performance of one LBD patient and one control is shown. Objects are listed according to descending weight.

exclude a handicap for the LBD patients suffering from dyslexia, because the ability to read was necessary to correctly identify the object as tea. As a consequence each regression comprised the data for 9 objects. We analyzed the ability and the precision of the anticipation by calculating analyses of variance (ANOVA) for the slopes (SL) and the coefficients of regression (R^2) with the between-subject factor Group (patients, controls) and within-subject factor block (1st, 2nd, 3rd). To avoid any influence of hand dominance on the interpretation of the findings, the groups performing with the left hand (controls left & LBD) and with the right hand (controls right & RBD) were tested separately.

The scatter of data of the linear regressions between GFRmax and weight was used to identify abnormal behavior in patients. As a cut-off a threshold of one standard deviation below the mean coefficient of regression (R^2) of the corresponding control group was considered to indicate impaired anticipatory skills in the task. In addition to linear regression analysis of the means of the parameters GFmax, GFRmax and T-liftoff across subjects were calculated and compared between groups using *T*-tests.

Finally correlations between the experimental results of LBD patients and their scores at conventional apraxia testing (pantomime tool-use and hand-, finger imitation) were calculated.

The level of statistical significance was set at $p < 0.05$.

3. Results

3.1. Grip force anticipation

Fig. 3 provides performance examples of one LBD patient and a corresponding control subject. It shows the time course of grip and load force as well as the corresponding grip force rate (GFR) for four selected objects during their first representation in Block 1. The control subject scaled the forces to the objects´ weight. The grip force developed faster and reached higher values for the heavier objects. A congruent order between signals and weight was apparent.

In contrast, the relationship between weight and force signals is less clear in the LBD patient's profiles. While the maximum grip force seemed to be scaled to the objects´ weight, the time courses of grip force rate did not show a relationship with object weight. For example, the maximum grip force rate for the filter was similar to the maximum rate for the book which was more than twice as heavy.

Fig.4 shows grip force scaling in selected subjects of each group (CL, LBD, CR, RBD). The maximum grip force rate (GFRmax) is plotted versus the weight of nine different objects lifted the first time in Block 1. As expected, both control subjects lifted the heavier objects with higher GFRmax values than the lighter ones. The relationship was close to linear in particular in the lower to middle range of weights. For the two RBD patients, the relation was not as apparent as for the control subjects, but still obvious. In contrast to that, LBD patient KL23 showed a different performance. GFRmax seemed to be at random without clear relationship to object weight. For example, the porcelain mug (270 g) was lifted with the same GFRmax as the book (805 g). This indicates that this subject did not anticipate the weight of the objects to be lifted. In the LBD patient HM21 a common trend of increasing GFRmax with increasing weight was obvious but variability was large. The six selected subjects where characteristic for their particular group.

In the next step of analysis, linear regressions were calculated for the relationship between GFRmax and objects' weight as well as between GFmax and weight for each subject and each block. The resulting parameters of the linear fits are displayed in Fig. 5 and were subjected to analyses of variance.

While the CL group showed a clear relationship between weight and GFRmax, the LBD group demonstrated less anticipation.

Analysis of variance for LBD patients and corresponding control subjects (CL) revealed significantly lower slope and R^2 (main effect group: slope-GFRmax: $F=8.0$, $p=0.009$; R^2-GFRmax: $F=5.6$, $p=0.026$). RBD patients demonstrated only a trend towards decreased weight anticipation compared to the control group

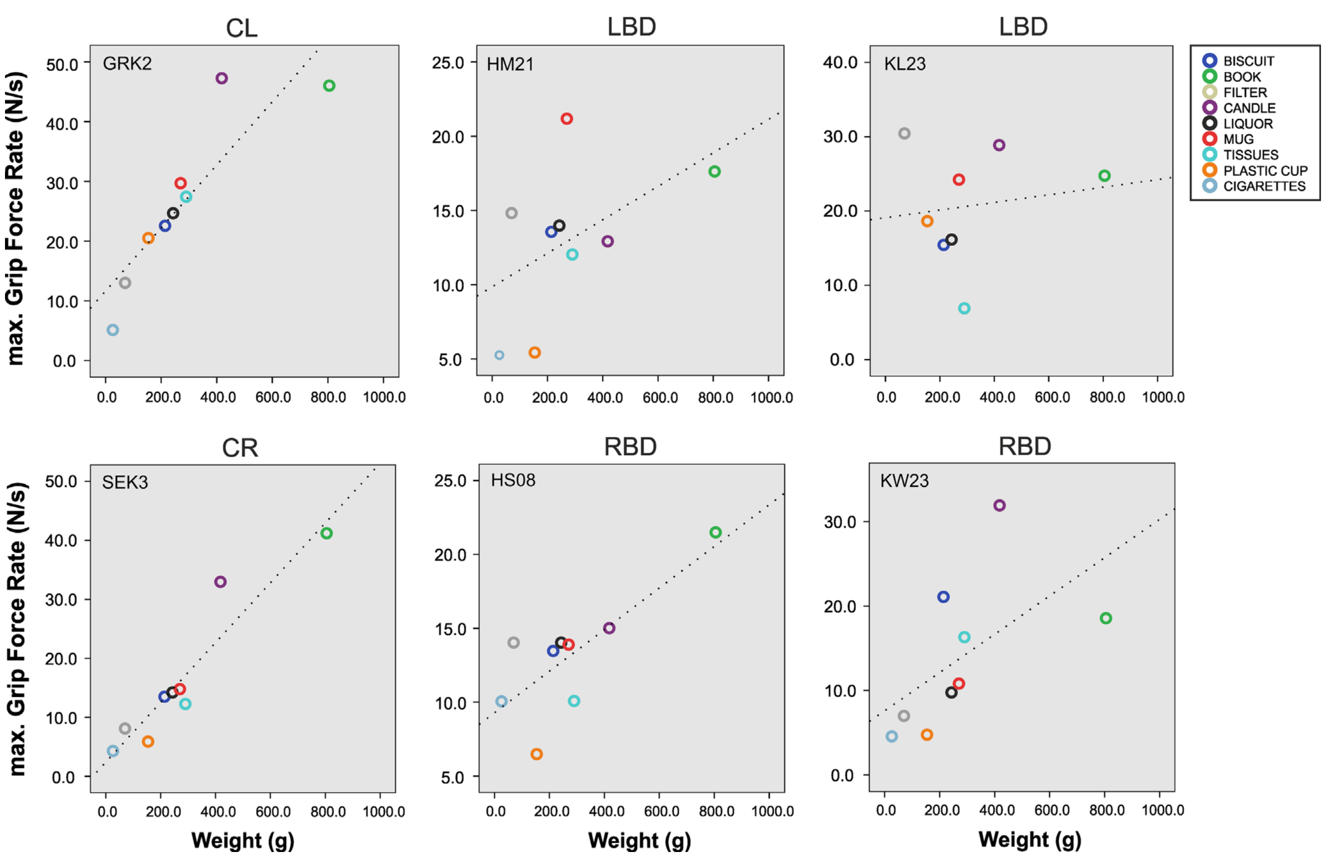

Fig. 4. Relationship between maximum grip force rate (GFR) and object weight. Results of one control (CL, CR) and two patients out of every group (CL, CR, LBD, RBD) for nine objects (ordered by increasing weight) during the first block are displayed. The line reveals the best linear fit with the coefficient of regression R^2 indicated.

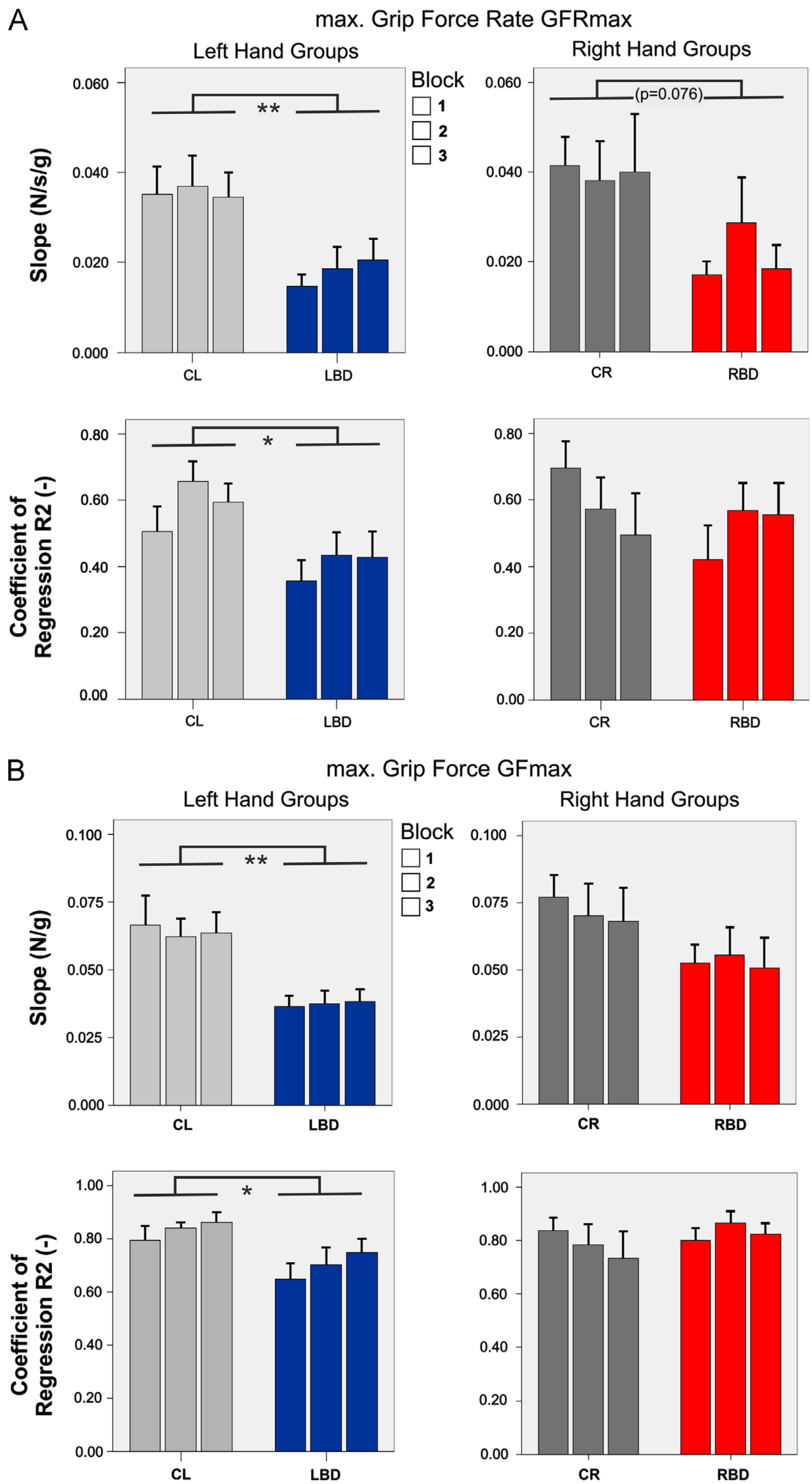

Fig. 5. Results of the linear regression between (A) maximum grip force rate (GFRmax) and weight as well as (B) maximum grip force (GFmax) and weight calculated from the individual performance within each block. Means and standard errors of the coefficient of regression R^2 and the slope are shown across the three blocks for the subject groups. $^{*}p \le 0.05$; $^{**}p \le 0.01$.

(CR) when the slope was considered, and they showed no statistically significant difference for the regression coefficient (main effect group: slope-GFRmax: $F=3.6$; $p=0.076$; R^2-GFRmax: $F<1$, $p>0.1$). No statistically significant main effect of block was detected, neither for the left hand groups (main effect block: slope-GFR: $F=0.5$, $p>0.1$, R^2–GFR: $F=2.3$, $p>0.1$) nor for the right hand groups (main effect block: slope-GFRmax $F<1$, $p>0.1$; R^2-GFRmax $F<1$, $p>0.1$). In addition, none of the interactions between groups and blocks revealed any significant effect (interaction group × block: LBD&CL slope-GFRmax: $F<1$, $p>0.1$; R^2-GFRmax: $F<1$, $p>0.1$; RBD&CR: slope-GFRmax: $F<1$, $p>0.1$; R^2-GFRmax: $F=2.0$, $p>0.1$).

The second parameter we investigated was the maximum grip force (GFmax). Its magnitude can be influenced by sensory feedback mechanisms because the maximum typically occurs after lift-off.

The ANOVAs for the maximum grip force also revealed differences between sides of unilateral brain damage. LBD patients had clearly difficulties to adjust grip force maximum according to object weight compared to their corresponding control group (main effect group: slope-GFmax: $F=11.8$, $p=0.002$; R^2-GFmax: $F=7.0$, $p=0.014$). In contrast, RBD patients showed no differences to their controls (main effect group: slope-GFmax: $F=2.7$, $p>0.1$; R^2-GFmax: $F=.12$, $p>0.1$).

3.2. Force magnitudes and duration

In separate analyses we compared the individual overall means of the three main parameters (GFmax, GFRmax and T-lifttoff) between the patients and the corresponding control groups. The average level of maximum grip force rate (GFRmax) and maximum grip force (GFmax) did not differ between patients and corresponding control subjects (left hand groups: *T*-test GFRmax: $F<1$, $p>0.1$, mean GFRmax LBD 15.5 N/s, SD 8.7 N/s; mean GFRmax CL 18.1 N/s SD 8.3 N/s; *T*-test GFmax: $F=2.91$, $p=0.099$, mean GFmax LBD 18.8 N, SD 6.2 N; mean GFmax CL 21.7 N, SD 7.3 N; right hand groups: *T*-test GFRmax: $F<1$, $p>0.1$, mean GFRmax RBD 14.9 N/s, 9.6 N/s; mean GFRmax CR 20.2 N/s, SD 6.8 N/s; *T*-test GFmax: $F<1$, $p>0.1$, mean GFmax RBD 20 N/s, SD 9.2 N, mean GFmax CR 25.3 N,SD 6.8 N).

T-tests for the average duration of the interval between grasp contact and lift-off (loading time T-lift off) revealed a non-significant trend for an increased duration in LBD patients compared to the corresponding control subjects ($p=0.054$, $F=4.1$; mean T-lift off LBD=216.4 ms, SD 71.6 ms; mean T-lift off CL=176.7 ms, SD=46.6 ms) and no statistically significant differences for the right hand group ($F>1$, $p>0.1$; mean T-lift off RBD=237.6 ms, SD 53.3 ms, mean T-lift off CR=185.4 ms, SD 62.8 ms). Similar loading times in LBD patients and control subjects suggests that the impaired grip force scaling reported above is not due to slowed and hesitant grasping and lifting in the patients. To further prove the absence of such a relationship we correlated the slope and regression coefficients of LBD patients with their average grip force rates and loading times. No significant correlation emerged (all $p>0.05$).

3.3. Lesions analysis

Fig. 6 shows the subtraction analysis for lesions of LBD patients with normal anticipation compared to those with impaired anticipation. Those LBD patients for whom the regression between maximum grip force rate and object weight had revealed coefficients (R^2) lower than one standard deviation below the average of the corresponding control subject group (CL: $R^2 \leq 0.39$) were considered impaired. The performance of seven LBD patients fell below the criterion value. Notably the seven patients were among the eleven patients who were identified when the same criteria (mean -1 SD) were applied to the slope of the regression (CL: slope ≤ 0.0179). As obvious from Fig. 6, the highest difference of lesion density between patients with impaired R^2 ($N=7$) and those with normal anticipation ($N=9$) was found in the left inferior frontal and the precentral gyri. Furthermore, lesions in the post-central gyrus and supramarginal gyrus seem to be associated with an impaired slope.

Applying the same criteria as in LBD patients to the group of RBD patients, three patients were considered impaired according to the threshold derived from the coefficients in the corresponding control group (CR: $R^2 \leq 0.31$) and only one of these patients revealed a slope below the criteria value (CR: slope ≤ 0.0129). Because of the small number of impaired RBD patients in addition to the relatively low total number of RBD patients with lesion information, we did not perform subtraction analysis in this patient group.

3.4. Relationship to apraxia

Fig. 7 shows the relationship between the measures characterizing the precision of grip force scaling (slope and R^2) and the apraxia scores assessed in the LBD patients (pantomime of tool-use test and hand imitation). Parameters of the regression of maximum grip force rates were used since this force measure best characterizes anticipatory scaling. Neither the slope of the linear regression nor the regression coefficient R^2 significantly correlated with the pantomime score (both $p>0.1$). Different from pantomime the score of hand imitation correlated strongly with both parameters of the linear regressions (slope: $R=0.56$, $p=0.024$, R^2: $R=0.72$, $p=0.002$). The corresponding correlations with the score of finger imitation did not approach statistical significance ($p>0.1$).

Applying the same analysis to the parameters of the regression for the maximum grip force confirmed the findings of an absent (to weak) correlation with the pantomime task and a strong correlation with the imitation task (slope vs. pantomime score: $p>0.1$; R^2 vs. pantomime score $R=0.49$, $p=0.052$; slope vs. imitation score: $R=0.64$, $p=0.008$; R^2 vs. imitation score: $R=0.76$, $p=0.001$).

Correlation analyses within the group of LBD patients did not reveal any significant relationship between the clinical parameters lesion size and months since onset of stroke (see Table 1) and the parameters of the regressions (all $p>0.1$). The same correlations with the RBD patients did also not reveal significant findings (all $p>0.1$).

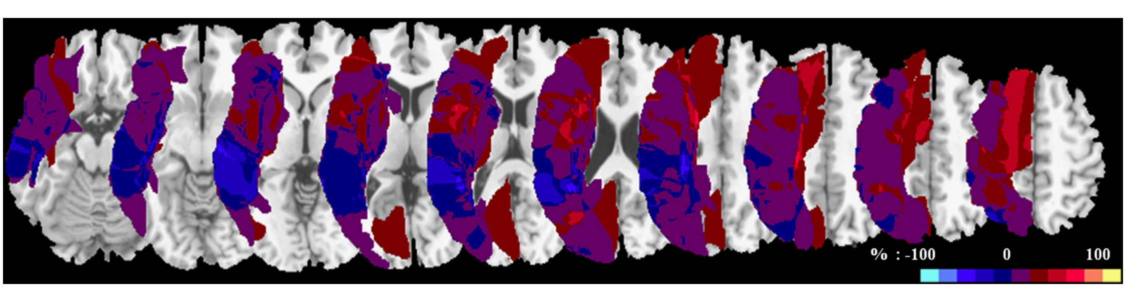

Fig. 6. Lesion subtraction. The overlay of 9 LBD patients who showed preserved grip force anticipation was subtracted from the overlay of 6 LBD patients who showed clearly impaired anticipatory scaling of GFR (for 1 LBD patient images were lacking) versus the other. The percentage of overlapping lesions of the patients with impaired anticipation after subtraction of the group with normal behavior is illustrated by 5 different colors coding increasing frequencies from dark red (difference=1–20%) to bright yellow (difference=81–100%). Each color represents 20% increments. Blue colors indicate regions damaged more frequently in the group of patients with normal behavior than in the group with impaired anticipation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

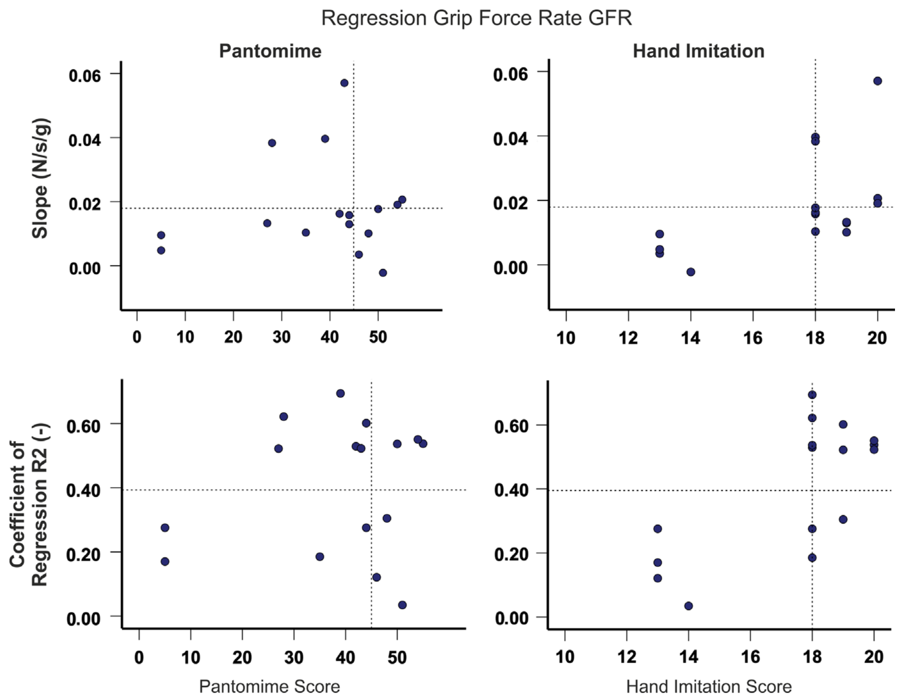

Fig. 7. Parameters characterizing weight anticipation (slope and R² of GFRmax) related to the pantomime of tool-use score and the meaningless gesture of hand imitation score. The vertical lines indicate boundary of normal performance as described in Goldenberg and Hagmann (1997) and Goldenberg et al. (2007). The horizontal lines indicate the limits of normal performance for grip force scaling defined as one standard deviation (of R^2 and slope) below the average of the corresponding control subject group.

4. Discussion

This study investigated the influence of unilateral brain damage on grip force anticipation when lifting everyday objects. Anticipatory force control is essential for skillful and fluent grasping of objects in everyday routine. Therefore, understanding the effects of brain lesions after stroke on anticipatory grasping is crucial for rehabilitation.

Patients with unilateral stroke and corresponding control subjects lifted everyday objects. In particular, the objects were well known from daily routine and the necessary grip force had to be inferred from learned associations between object identity and the object characteristics relevant for grasping. Two usually highly effective cues were controlled for, namely experience with the same object from the preceding lifting trial and object size, thus these cues were not helpful for participants in the present design. First, each lift was preceded by lifting of a neutral object and also the second-last object was never equal to the current one so that refinement of short-term sensory motor memory as for constant objects was not possible (Flanagan, King, Wolpert, & Johansson, 2001; Johansson & Westling, 1988; Witney, Goodbody, & Wolpert, 2000). Second, a set of objects was selected in a way that size alone did not provide reliable information about the object's weight. The maximum grip force rate before liftoff was analyzed since it is known to be a highly sensitive measure to indicate successful preplanning of manual interaction with familiar objects (Gordon et al., 1991b; Hermsdörfer et al., 2011; Johansson & Westling, 1988; Li et al., 2009; Nowak, Timmann, & Hermsdörfer, 2007).

The comparison of the different groups (left brain damage, right brain damage, corresponding controls) led to the finding that left brain damage impairs anticipatory skills during manipulation of everyday objects. The current study also revealed associations between impaired force scaling and apraxia scores. Notably, the deficient anticipatory dexterity correlated strongly with a test of hand imitation and not with a test of pantomime of tool-use. These central findings are discussed below.

4.1. Anticipation of objects properties when lifting everyday objects

In control subjects and most of the RBD patients there was a nearly linear relationship between grip force measures and object weight, i.e., higher grip forces and grip force rates were applied for heavier objects, whereas lower forces and force rates were used for lighter objects. In contrast, the increase of grip measures with object weight was significantly smaller and the data scatter was significantly larger in LBD patients, as obvious from lower slopes and lower coefficients of the linear regressions compared to control subjects. In some LBD patients grip force rate profiles seemed at random with clearly inappropriate initial grip forces production for some of the objects.

Since the objects were part of the daily routines (e.g. tooth brush is used on daily basis, even in hospital) and all subjects could name or point at the single objects, a pure inability to recognize the objects can most probably not account for the deficits of LBD patients. The impairment rather seems to results from an inability to retrieve or process grasp-relevant information from the object identity. A specific impairment in anticipating the properties of everyday objects during lifting was also reported by Dawson et al. (2010) in two out of six tested LBD patients. Comparable to our finding for grip force, the vertical lifting force did not vary with the weight of the objects.

Instructing subjects to perform the task fluently and quickly avoided that impaired anticipation results from a probing strategy when the object is tactually explored before lifting. Indeed the time between finger contact and lift-off as well as the average maximum grip force rate was not significantly different in control subjects and any of the patient groups. A trend for prolonged loading times in LBD patients may be indicative of mild general hesitations, it did however not correlate with deficits in anticipation (see Section 3.2). Also an increased average grip force level could not be a confound leading to imprecise force scaling since the average force level was similar in control subjects and patients groups (Dubrowski et al., 2005). The finding of normal average grip force levels is in contrast with reports of increased ipsilesional grip forces in stroke patients during comparable lifting task with the ipsilesional hand (Nowak et al., 2007; Quaney, Perera, Maletsky, Luchies, & Nudo, 2005). The fact that a mechanically more stable three finger grip instead of a two-finger index-thumb grip was used previously may be responsible for the discrepant findings (for a similar discussion see also Li et al., 2011).

Other studies show that there is no clear deficit of anticipatory force scaling when LBD patients lifted neutral objects of different size (Dawson et al., 2010; Li et al., 2011). Independent of the side of brain damage, stroke patients used higher grip forces and grip force rates when lifting a large neutral plastic box and lower force magnitudes when lifting a smaller box for the first time in a size-weight illusion paradigm. On average, force differences between the two boxes were similar between patients and control subjects (Li et al., 2011). A possible reason for the discrepant findings between lifting neutral and everyday objects in LBD patients may be that object size can still be processed. If however size is not a reliable cue, performance deteriorates – as is implicated by the results in the current study.

Our findings are reminiscent to a recent study in stroke patients on learning visuomotor associations during object lifting (Bensmail, Sarfeld, Ameli, Fink, & Nowak, 2012). That study revealed, that left brain damage impairs the ability to establish an association between a symbolic cue and corresponding object weight (Bensmail et al., 2012). Patients scaled their grip force according to the weight of the preceding object and disregarded the symbolic weight cue for the current object. While only the ipsilesional hand was tested in the present study, both hands could be tested in the study by Bensmail et al. (2012). Consistent with the concept of effector-independence of higher order motor deficits, force scaling was impaired for both hands. Findings of this and our present study suggest that the left hemisphere is responsible for encoding and/or retrieving learnt semantic object information for the purpose of manipulation. In contrast, as noted above, the processing of size information seems less vulnerable to left brain damage resulting from media artery stroke (Li et al., 2011).

The left hemisphere controls the preferred hand and is dominant for language. The deficiency of associating attributes of the objects with selected parameters of grip formation is reminiscent of a rich literature demonstrating that patients with left hemisphere damage and aphasia have difficulties to associate stimuli according to selected attributes rather than to global similarity (Vignolo, 1990). The inability to associate the identity of objects with their weight may be an expression of such a pervasive deficit.

Notably, the study of Bensmail et al. (2012) revealed a deficit of visuomotor association learning on the contralesional left hand of RBD patients, while the ipsilesional right hand of RBD patients was unaffected. We observed a trend for impaired force scaling on the ipsilesional side in the group of RBD patients obvious as a reduced slope of the linear regression for grip force rates compared to control subjects. Therefore, both studies also conform in finding a deficit of anticipatory force scaling after damage in RBD patients.

As can be inferred from the indirect comparisons with the respective control groups, the deficit following right brain damage is however clearly milder compared to left brain damage. Whether the behavioral deficit in both patient groups has the same cause indicating similar control processes in the left and right brain remains speculative. One specific right brain deficit that could have influence object perception is visuospatial neglect. Since symptoms of neglect were present in most of the patients of the RBD group and the severity of neglect was not further differentiated (see Table 1) we could not test for an association of the mild force scaling deficit with the presence of neglect. One should also consider that the failure to find statistically significant differences between RBD patients and control subjects may have been affected by the smaller sample size of this patient group. We therefore focus our further discussion on the results of the LBD group leaving open the possibility that future studies in larger groups of RBD patients may find deficits in anticipatory grip force following RBD for any of the reasons mentioned above.

Force scaling deficits in the LBD group manifested not only in the grip force rate but also in the maximum grip force. Since the maximum grip force occurs after lift-off, feedback information about object weight will typically be available. Our data suggest that feedback information could not be effectively processed to ameliorate the effects of imprecise initial force scaling on maximum grip forces. It cannot be resolved from the present data, whether this is due to a lack of time to process information or related to brain damage. Consistent with the later explanation, Quaney et al. (2005) reported a frequent increase of the grip force on the ipsilesional hand in stroke patient while control subjects tended to relax the grip during continued holding of objects. On the other hand, LBD patients are able to adjust grip forces according to sensory experience from the preceding lifting trial arguing against a deficit in processing relevant afferent information (Li et al., 2011; Dawson et al., 2010).

No improvement of force scaling was obvious across three repeated blocks of lifting trials. For the group of healthy subjects this is consistent with previous findings (Hermsdörfer et al., 2011). In patients, successful adaptation to object properties was demonstrated during repeated lifting of everyday and neutral objects (Dawson et al., 2010) and of two differently-sized objects in a size-weight-illusion paradigm (Li et al., 2011). Therefore LBD patients seem to be able to adjust their grip force according to information from previous lifting trials. However, the present design with twelve objects presented in random order seems to exceed the capacity to establish stable associations. Given the relevance of object manipulation in everyday performance, the conditions that maximize the patients' capacities should be evaluated in future studies.

4.2. Impaired anticipation and apraxia

The finding of impaired anticipatory force scaling following damage to the left brain raises the question of whether the deficit is related to apraxia (see Introduction). Our data provide only partial support for the existence of a more general correlation. The pantomime score was considered the most relevant clinical measure for the investigation of this relationship because it is an established and highly sensitive measure of apraxia which tests knowledge about tools and about manipulation of objects of everyday life (Goldenberg et al., 2003; Hanna-Pladdy, Heilman, & Foundas, 2001; Liepmann, 1908; Raymer, Maher, Foundas, Heilman, & Rothi, 1997). The correlation between the two measures reflecting precision of force scaling and pantomime score were not significant (Fig. 6). Low correlations were mainly due to a single patient with normal pantomime score but absent force scaling, but there were also patients with moderate pantomime deficits and high scaling skill (6 patients, for more information see Table 1). Several arguments may account for the limited predictive value of pantomime. Abstract knowledge about object use, as requested for pantomiming, may not be informative for physical interaction with the object. Indeed, preserved real tool-use despite severe pantomime deficits have frequently been reported (see Introduction). Evidence for the opposite dissociation of preserved pantomime and impaired real tool-use is however very limited (Motomura & Yamadori, 1994). Thus, a score of real tool-use, which was not assessed in the present study, would probably also not have revealed a perfect correlation. In addition, knowledge about how to manipulate tools in the prototypical way may be processed differently from knowledge about the physical properties necessary for manipulation. A classical study in healthy subjects has for example shown that the effect of necessary force to carry an additional load was incorrectly incorporated into the imagination of walking a certain distance that otherwise was quite precise (Decety, Jeannerod, & Prablanc, 1989). In a size-weight-illusion paradigm, the grip forces to lift objects of different size but equal weight adapts to the weight, while the illusory perception of a heavier weight for the smaller object persists (Flanagan & Beltzner, 2000) Thus, some of the processes related to the retrieval and storage of object information relevant for the use as a tool and for hand-object interaction may be closely related while others are distinct.

Somewhat surprisingly, a strong correlation was found between the hand imitation score and the precision of force scaling. Hand imitation is a sensitive test of apraxia but it does not involve actions with objects (Goldenberg, 2009). Goldenberg reasoned that hand imitation puts demands on categorical apprehension of spatial relationships between multiple objects or between multiple parts of the objects. In hand imitation this process enables the coding of body parts (Chaminade, Meltzoff, & Decety, 2005; Goldenberg & Karnath, 2006; Goldenberg & Strauss, 2002; Peigneux et al., 2004), during force scaling it may support the coding of relevant features of objects for hand-object interaction. Thus at a certain level both processes may be dependent on the integrity of similar structures. It should be noted that the lesion data are equivocal with respect to this interpretation. Inferior parietal lesions have been associated with apraxic hand imitation deficits (Goldenberg & Karnath, 2006), while patients with impaired scaling exhibit rather distributed lesions that involve the inferior parietal cortex but also other brain areas (Fig. 7).

4.3. Neural correlates

Dawson et al. (2010) found that lesion in parietal and adjacent temporal areas were particularly responsible for scaling deficits in their sample of six patients. Our analysis failed to accentuate either of the described single areas thought to be responsible for the deficit. While in the present study parietal areas were damaged in many of the impaired patients,

symptom-related lesion were predominantly found in anterior regions such as inferior frontal gyrus and premotor cortex. Ventral premotor cortex and the opercular portion of IFG have been proposed to be the repository of a “vocabulary” of motor actions (Binkofski et al., 2000; Rizzolatti & Luppino, 2001), which serves for translating information about object properties and action goals into combinations of motor programs. Similarly impaired grasping tools according to their function is predominantly associated with lesions in the IFG (Randerath et al., 2010). However, our lesion analysis still has to be considered with care due to the relatively low number of patients. Given the complexity of the tasks, involving steps like object identification, association of relevant object features and interaction with the motor system a distributed network involved in anticipatory force-scaling seems more feasible. Tasks involving grasping object for manipulation have been shown to activate recurrent frontoparietal networks (Davare, Rothwell, & Lemon, 2010), grip force control activates various frontal and parietal areas (Chouinard & Goodale, 2009) and the learning of visuomotor-associations involves various areas including the dorsal premotor area and the intraparietal gyrus (Chouinard & Goodale, 2009; Taubert et al., 2010).

5. Conclusion

Our study revealed a deficit in the anticipatory scaling of the grip force when everyday objects are lifted that is mainly associated with left brain lesions. The deficit obviously shares representations with various manifestations of apraxia but also seems to involve independent and specific control processes. In many patients with severe contralesional paresis any limitation of the function of the non-paretic hand is critical for quality of life. Therefore, considering the high clinical relevance of the currently found deficit should gain increased attention during therapy.

Acknowledgments

The study was supported by the Grants from the Federal Ministry of Education and Research (BMBF, Project 01GW0572) and from the German Research Foundation (DFG, Project HE 3592/7-1).

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Danksagung

Mein Dank gilt vor allem meinem Doktorvater
Prof. Dr. Joachim Hermsdörfer für seine tatkräftige und geduldige Unterstützung. Stets stand er mit Rat und Tat zur Seite und zeigte mir, welche Freude, wissenschaftliche Arbeit machen kann.

Ich danke allen Patienten und gesunden Probanden für ihr geduldiges Hochheben aller möglichen Alltagsgegenständen. Mein Dank gilt hier im speziellen den Patienten, die sich trotz ihrer Handicaps bereit erklärten, an der Studie teilzunehmen. Mein Dank gilt außerdem Dr. Jennifer Randerath. Mit ihrem großen Wissen bezüglich Apraxie und Werkzeuggebrauch stand sie mir stets beratend zur Seite, zudem danke ich für ihre Mitarbeit im Rahmen der Läsionsanalyse. Ihre Unterstützung kam immer prompt und umsichtig, obwohl wir uns teilweise auf verschiedenen Kontinenten befanden.

Im Weiteren danke ich meinem Mann Florian Hörmann und meiner Familie, die mir stets beratend zur Seite standen und mir tatkräftig Freiräume für diese Arbeit schufen.