Article:

McIntosh, RD, Mon-Williams, M orcid.org/0000-0001-7595-8545 and Tresilian, JR (2018) Grasping at laws: Speed-accuracy trade-offs in manual prehension. Journal of Experimental Psychology: Human Perception and Performance, 44 (7). pp. 1022-1037. ISSN 0096-1523

https://doi.org/10.1037/xhp0000512

Author copy, article accepted *Journal of Experimental Psychology, Human Perception & Performance* 27/10/2017

Grasping at laws: speed-accuracy trade-offs in manual prehension

Robert D McIntosh[1]*, Mark Mon-Williams[2] & James R Tresilian[3]

[1]Human Cognitive Neuroscience, Psychology, University of Edinburgh, UK

[2]School of Psychology, University of Leeds, UK

[3]Department of Psychology, University of Warwick, UK

Word count of body text: 8636

*Correspondence:

Dr. Robert D McIntosh

Psychology, University of Edinburgh

7 George Square, Edinburgh, EH8 9JZ

Tel: +44 131 6503444

Fax: +44 131 6503461

r.d.mcintosh@ed.ac.uk

Supplementary materials: Full data for this study are available under the first author's account at the Open Science Framework: https://osf.io/v2rqe/

Abstract

Most of human performance is subject to speed-accuracy trade-offs. For spatially-constrained aiming, the trade-off is often said to take the specific form of Fitts' law, in which movement duration is predicted from a single factor combining target distance and target size. However, efforts to extend this law to the three-dimensional context of reaching to grasp (prehension) have had limited success. We suggest that there are potentially confounding influences in standard grasping, and we introduce a novel task to regularise the direction of approach and to eliminate the influences of nearby surfaces. In six participants, we examined speed-accuracy trade-offs for prehension, manipulating the depth (in the plane of the reach), height (orthogonal to the reach) and width (the grasped dimension) of the target object independently. We obtained lawful relationships that were consistent at the group and individual levels. It took longer to reach for more distant objects, and more time was allowed when placing the fingers on a contact surface smaller in either depth or height. More time was taken to grasp wider objects, but only beyond a critical width that varied between individuals. These speed accuracy trade-offs showed substantial departures from Fitts' law, and were well described by a two-factor model in which reach distance and object size have separate influences on movement duration. We discuss empirical and theoretical reasons for preferring a two-factor model, and we propose that this may represent the most general form of speed-accuracy trade-off, not only for grasping but also for other spatially-constrained aiming tasks.

Keywords: aiming; grasping; prehension; speed-accuracy trade-off; Fitts' law.

Public significance statement: This study establishes that the time equired to reach and grasp an object can be predicted, with very high reliability, from the distance of the reach, and the size of the object in three dimensions.

Introduction

Skilled movements require consistency and flexibility. These basic features are recognised by virtually all theorists (e.g. Bullock & Grossberg, 1988; Feldman & Levin, 2009; Saltzman & Kelso, 1987; Schmidt, 1975; Todorov, 2004), but precise descriptions of the invariant aspects of performance and the laws governing adjustment to circumstances have been elusive. A prominent example is the speed-accuracy trade-off for moving to stationary targets. This is often said to be captured by Fitts' law, which, in its original formulation, states that the time taken to move to a target (movement time: MT) is directly proportional to the logarithm of the ratio of the target distance (amplitude: A) to target size in the reach direction (width: W) (Fitts, 1954). Performance in some tasks conforms quite closely to Fitts' law, most notably the one dimensional aiming tasks originally studied by Fitts himself (1954; Fitts & Peterson, 1964), in which target width constrains endpoint accuracy in the direction of movement. But unidimensional tasks are seldom encountered in everyday life, and tasks that more closely resemble everyday activities, such as moving the hand through three dimensions to contact a flat surface, or reaching to grasp a solid object, have been found to be less well described by Fitts' law (e.g. Bohan, Longstaff, Van Gemmert, Rand, & Stelmach, 2003; Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Jüngling, Bock, & Girgenrath, 2002; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990; Zaal & Bootsma, 1993). Despite its textbook status (e.g. Schmidt & Lee, 2011), almost as many published studies report deviations from Fitts' law as report conformity to it (Plamondon & Alimi, 1997; Tresilian, 2012), suggesting that it is not a firm general foundation for models of aimed movements.

However, it is almost universally observed that aiming movements take longer for targets that are more distant and/or smaller (though not necessarily smaller in the reach direction: MT = $f_{[a,b,\ldots,n]}(\text{Size}^{-1}, \text{Distance})$, where $f()$ is a monotonically increasing function and [a,b,…,n] is a set of n parameters, constant for an individual performing a given task. Fitts' law could be an approximation to this general law (Beamish & Bhatti, 2006), for cases in which accuracy is constrained by target size in the reach direction only. Hermann & Soechting (1997) argued that the discovery of such a general relationship would be “profound”; but they considered it unlikely, because multi-joint movement durations are determined by factors other than target size and distance, such as biomechanical factors that depend on the way the movement is executed. However, whilst these factors add intricacy, they need not preclude a general law for speed-accuracy trade-offs if they can be accommodated by its task-specific parameters, much as the intercept (a) and slope (b) parameters of Fitts’ law depend on the mass to be moved (Fitts, 1954; Hoffmann, 1995) and the muscles and joints involved (e.g. Langolf, Chaffin, & Foulke, 1976). A complete description of the speed-accuracy trade-off would require statements about how these parameters depend on the precise movement task; but the general law could be fitted to a dataset provided that the task is the same for all conditions in the experiment (i.e. that the task-specific parameters are held constant). To investigate the possibility of a more general speed-accuracy trade-off for spatially-constrained aiming, a good task to study would be a well-practiced aiming task that constrains terminal accuracy in more than just the reach direction, such as reaching to grasp a stationary object (prehension).

Speed-accuracy trade-offs in prehension

The present study will specifically examine speed-accuracy trade-offs in prehension, not only to explore the plausibility of a general speed-accuracy trade-off for spatially-constrained aiming, but also because prehension is a vitally important human skill in its own right. The dominant model of prehension distinguishes between transport and grasp components, with the transport of the hand considered as an aiming movement, and the formation of the grasp superimposed in time

(Jeannerod, 1981, 1986).[1] Several studies of the speed-accuracy trade-off in prehension have been interpreted in terms of Fitts' law, but in fact show a poor correspondence with the standard form of Fitts' law (e.g. Bootsma, Marteniuk, MacKenzie, & Zaal, 1994; Jüngling, Bock, & Girgenrath, 2002; Marteniuk, Leavitt, MacKenzie, & Athenes, 1990; Zaal & Bootsma, 1993). For instance, Bootsma and colleagues (1994) suggested that the side length of the contact surface governs movement time for grasping square cross-section blocks; but the proportion of variance captured by substituting this length for W in Fitts' equation was only .46 for their group of five participants (individual r^2 varied from .15 to .41), falling short of the high values expected from a successful application of Fitts' law ($r^2 \geq .90$: see Table 3, Plamondon & Alimi, 1997).

In re-examining this issue, we can suggest at least three possible reasons that Fitts' law has not yet been convincingly shown for prehension. First, the key assertion of Fitts' equation is that target distance and size have non-additive effects on movement time, and this seems more plausible for unidimensional aiming than for tasks in which the target constrains accuracy both in the reach direction and perpendicular to it. Indeed, for bi-dimensional aiming, Fitts' law may give a relatively poor fit ($r^2 << .90$ in Bohan et al., 2003; Hoffman & Shiekh, 1994; Shiekh & Hoffman, 1994), and independent effects of target distance and size have frequently been identified (Bainbridge & Sanders, 1972; MacKenzie & Graham, 1997; Sheridan, 1979). Prehension might just be too complex to be captured by a law formulated originally for unidimensional tasks.

A second, more fundamental concern is that Fitts' law may not the best general law for spatially-constrained aiming, even in the unidimensional case, because it conflates separable effects of target distance and size. Welford (1968) was one of the first to claim that movement time data for unidimensional aiming are better explained by allowing amplitude and size to have independent

[1] An alternative idea is to model prehension as anatomically-yoked aiming movements of the grasping digits (Smeets & Brenner, 1999; Verheij et al., 2012), such that transport and grasp parameters would not be controlled directly, but would be emergent features of a control scheme focused on the individual digits. We consider these *digit-control* models of prehension more fully in later Discussion.

effects. He thus proposed a two-factor model: $MT = a + b \cdot \log_2 A + c \cdot \log_2 W$ (where a, b and c are constant for an individual performing a given task). Welford's argument was not merely that a two-factor model gives a better fit to the data; a (slightly) better fit could be expected just from the fact that the model has one more free-fitting parameter than Fitts' equation. Rather, his claim was that A and W had independent effects, as indicated by the fact that the movement time data did not form one straight line when plotted against Fitts' index, but distinct straight lines grouped by target distance. This pattern is visible in many aiming studies, even in some that claim conformity with Fitts' law (e.g., Gan & Hoffman, 1988; Kerr & Langolf, 1977). Thus, whether the task is uni- or multidimensional, there is reason to think that the effects of target distance and size are independent, so that a two factor model may always be more appropriate than Fitts' law.

A third possibility is that prior studies of speed-accuracy trade-offs in prehension might have been confounded by certain non-essential features of the standard laboratory grasping task. In the standard task, the hand and the target object both begin on a tabletop, which encourages a complex three-dimensional path of transport: the typical movement is bowed, heading forward and upwards then descending diagonally towards the object (Jeannerod, 1981; Verheij, Brenner, & Smeets, 2012, 2013). This curvature reduces experimental control over the transport distance, which will exceed the straight-line path to the object. It also makes the final angle of approach unpredictable, and thus loosens experimental control over the object's *effective* size and shape for the grasping hand. There might be a square contact surface on each side of an object (e.g. Bootsma et al., 1994), but an oblique angle of approach would mean that the *effective* surface is a tilted square. Moreover, a downward component to the final approach will allow the tabletop to stop the fingers at the object, effectively removing terminal accuracy constraints in the plane parallel to the approach.

The present study

These task considerations suggest that, to best evaluate speed-accuracy trade-offs in grasping, we should move from the standard tabletop design to an arrangement in which we can more confidently define the reach distance and target size. We thus adopted an 'aerial' grasping task, in which the target object and the hand are elevated to the same height, with no supporting surfaces to influence movement. Verheij et al. (2013) have shown that the typical vertical curvature of prehension transport is due to constraints imposed by the presence of surfaces at the starting point of the hand. Our task removes these constraints, so a more direct path should be preferred; in addition, the absence of a supporting surface for the target means that no end-stop is available for the fingers.

There is an indefinite variety of objects that might be presented, and a range of possible grasp postures. We restrict our analysis to the grasping of cuboids, using a one-handed precision grip to grasp the object side-to-side between index finger and thumb (Figure 1). In this configuration, the depth, height and width of the object impose distinct constraints on the accuracy of digit placement. We will study the influence of each of these dimensions by manipulating them independently. From first principles, and informed by prior literature, we can make predictions about the directional influence that each object dimension should have on movement duration.

Taller objects demand less (vertical) directional accuracy than shorter ones; so, with depth and width held constant, we would expect movement time to decrease with height. This general pattern has been observed for simple *aiming* movements whenever the speed-accuracy trade-off for directional accuracy has been examined (e.g. Beggs & Howarth, 1972; Hoffmann & Sheikh, 1991), and in one study of grasping in which height was varied (Tresilian & Stelmach, 1997). In contrast to the directional constraint imposed by object height, the depth of the object corresponds to accuracy in the reach direction in standard aiming. However, unimanual grasping entails an added constraint on freedom of movement in this direction, because the finger and thumb are linked together, so the object would eventually come into contact with the parts of the hand between finger and thumb. This constraint is more severe for wider objects, because the hand must open more fully, which means that depth and width do not place fully independent constraints on accuracy. However, provided that object depth does not exceed the freedom of movement in the reach direction, movement time would be expected to decrease with depth. This expectation is broadly consistent with prior observations (Bootsma, Marteniuk, & MacKenzie, 1994; Borchers et al., 2014).

The case of object width is even less straightforward. Width does not affect the contact surfaces for the digits directly, but it does interact with the distance between the digits (the grip aperture) to constrain directional accuracy in the horizontal dimension. The difference between the grip aperture and the object width sets a tolerance for horizontal error in wrist positioning, within which neither digit is in danger of colliding with the front of the object. In this respect, the grasping task resembles the task of placing a washer on a peg, which is known to conform approximately to Fitts' law (Fitts, 1954). But whereas the error tolerance is fixed in the washer-peg task, a person can adjust the error tolerance of grasping by changing their grip aperture; for this reason the aperture-width difference can be considered a safety margin (Jakobson & Goodale, 1991; Schlicht & Schrater, 2007; Wing, Turton, & Fraser, 1986). In principle, the grip aperture could be adjusted to maintain a constant safety margin across objects of different widths, so that the accuracy demands would not change. This strategy would reach its limit as object width approached the largest that could be grasped unimanually. Thus, below some critical width, movement time might be relatively constant across object widths; above this critical width, movement time should increase for wider objects. Previously reported effects of object width on movement time are somewhat varied. Bootsma and colleagues (1994) found that movement time was increased only at a width that approached the graspable limit (90 mm), but others have reported significant effects for widths below 60 mm (Borchers et al., 2014; Jakobson & Goodale, 1991).

We aimed to test the predictions developed above, manipulating each dimension of the target object independently, and using an aerial grasping procedure to eliminate confounding influences of other nearby surfaces, encouraging a more direct approach (Verheij et al., 2013). This allowed us to examine the speed-accuracy trade off separately for each object dimension, and thus to assess the degree to which prehension is described by a Fitts' law model. It has been standard practice, for simple aiming, to assess how well Fitts' equation or other models fit data from small groups of participants, typically between 4 (e.g. Meyer, Abrams, Kornblum, & Wright, 1988) and 18 (e.g. Adam, Mol, Pratt, & Fischer, 2006; Zelaznik, Mone, McCabe, & Thaman, 1988). This group strategy was applied in Fitts' original studies (Fitts, 1954; Fitts & Peterson, 1964) and followed by researchers seeking to test the generality of Fitts' law (e.g. Adam et al., 2006; Hoffmann, Drury, & Romanowski, 2011; Jagacinski, Repperger, Moran, Ward, & Glass, 1980; Langolf et al., 1976; I. MacKenzie & Buxton, 1992; Murata & Iwase, 2001; Wu, Yang, & Honda, 2010), or investigating the speed-accuracy trade-off in other types of task (e.g. Newell, Hoshizaki, Carlton, & Halbert, 1979; Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). It has been rare to fit these models to individual participant data, except when a single participant only was studied (e.g. Beggs & Howarth, 1972; Crossman & Goodeve, 1983), despite the fact that these models are normally taken to reflect invariant aspects of the underlying organisation of the nervous system (e.g. Bullock & Grossberg, 1988; Harris & Wolpert, 1998; Meyer et al., 1988; Plamondon & Alimi, 1997; Schmidt et al., 1979). In seeking to describe such fundamental regularities, the group strategy would be adequate only if it were known that individuals do not depart from the group pattern in idiosyncratic ways. Therefore, in the present study, we fit models of the speed-accuracy trade-off to individual participant data as well as to the average performance of the group.

Methods

Participants

Six participants performed repeated grasps across a variety of experimental conditions; see *Statistical strategy, and sensitivity* for sample size considerations. Two were female and four male (aged 19-25 years), and all were right-handed by self-report. The study was conducted at the Perception and Motor Systems Laboratory, Department of Human Movement and Sports Science, University of Queensland, and carried out in accordance with the Declaration of Helsinki, with approval from the University of Queensland's Medical Ethics Committee.

Apparatus

The testing board had a metal lever at its near edge, which the participant lifted by its tip before each trial. This lever, when pinched between finger and thumb at the top of its range, placed the digits 220 mm above the board, about 200 mm in front of the sternum. This was the hand's start position. Stimulus objects were natural pine wooden cuboids, mounted centrally on thin metal rods. Each rod fitted into holes drilled in the board, elevating the centre of the object by 220 mm, and placing it 170, 320 or 470 mm directly in front of the start position. Objects were to be grasped side-to-side between the finger and thumb of the right hand (Figure 1).

Initially, three sets of objects were used. Within each set, one dimension varied and the others were held constant at a size unlikely to limit movement time. The three sets manipulated: *depth* (D: the extent of the object in the plane parallel to the reach); *height* (H); and *width* (W) (the extent of the object in the planes orthogonal to the reach). Therefore, the contact surface area for the finger and thumb was determined by depth and height, whilst width was the grasped dimension and thus determined the grip aperture required to hold the object. The three sets had five objects each, one dimension varying within each set:

Depth set: **D = 5, 10, 20, 40 or 90 mm**; H = 90 mm, W = 20 mm.

Height set: D = 90 mm; **H = 5, 10, 20, 40 or 90 mm**; W = 20 mm.

Width set: D = 90 mm; H = 90 mm; **W = 5, 10, 20, 40 or 90 mm**.

An additional set of six objects of varying width was later created, to investigate the influence of object width between 40 and 90 mm. This set of objects was presented at the middle reach amplitude only (320 mm). We distinguish this additional *width** set by an asterisk:

Width* set: D = 90 mm; H = 90 mm; **W = 40, 50, 60, 70, 80 or 90 mm**.

Procedure

Each participant completed the initial three object sets in separate experimental blocks, on the same or a different day. Each participant followed a different one of the six possible initial block orders, and all re-attended the laboratory on a subsequent day to complete the additional *width** block.

Within each block for the main stimulus sets, each of the five objects was presented at each of the three reach distances nine times, for a total of 135 experimental trials. Trial order was generated by shuffling the fifteen trial types within each of nine successive epochs of 15 trials, so that each condition occurred once within each epoch. The nine epochs were preceded by one epoch of 15 practice trials. The additional *width** block followed the same pattern, except that there were ten epochs of six trials (six object widths at 320 mm) for 60 experimental trials, preceded by one epoch of six practice trials.

The experimenter prepared for each trial by mounting the stimulus object in position; and the participant prepared by lifting the start lever, so that the hand was placed in its start position.

The experimenter counted “2-1-drop”, whereupon the participant dropped the lever onto a muffling pad, leaving the hand in its aerial start position. After 1500 ms, a tone cued the participant to respond, and motion tracking began. The task was to grasp the object quickly and accurately, as if intending to lift it from its mounting; the importance of quick grasping was emphasised. Two seconds later, a higher tone marked the end of motion tracking, and the participant released the object to prepare for the next trial. Trials with false starts or other procedural errors were re-run immediately.

Kinematic recording and analysis

Prehension movements were recorded by two co-registered Optotrak 3020 motion-tracking units with complementary views to ensure continuous marker visibility. These sampled the 3D positions of three 7 mm infra-red emitting diodes (IREDs), attached to the wrist (styloid process of radius) and to the distal phalanxes of the thumb and index finger, at a sampling rate of 200 Hz.

Raw IRED coordinates were filtered by a dual pass through a second order Butterworth filter with a cut-off frequency of 20 Hz. Across all participants and object sets, 1.55% of trials were excluded due to lost IRED signals. For all other trials, tangential speed of the reach was computed from the wrist IRED, and from this the onset of the movement was estimated using the algorithm described by Teasdale et al. (1993; algorithm b). Grip aperture was calculated as the distance between finger and thumb IREDs. Movement offset was estimated from grip aperture during the terminal phase of grip closure, as the sample in which grip closure exceeded 99.75% of the difference between the maximum and terminal apertures.

The following variables were extracted: movement time (MT) from movement onset to offset; peak speed (PS) of the wrist during the movement; time to peak speed (TPS) from movement onset; time after peak speed (TAPS) to movement offset; maximum grip aperture (MGA) between finger and thumb during the movement. MGA values were corrected for IRED position, by subtracting the aperture recorded with the finger and thumb pinched together. MGA values thus represent the true separation between the digits, not between the IREDs.

Statistical strategy, and sensitivity

Fitts' law is used to predict average movement time in spatially constrained aiming tasks; its successful application will typically capture more than 90% of the variance (see Table 3, Plamondon & Alimi, 1997). Our main analyses tested the goodness of fit of Fitts' law, and alternative two-factor models, at the group and participant levels, for the *depth*, *height* and *width* stimuli. In considering the appropriate sample size for these analyses, the most relevant consideration is not the number of participants, but the number of conditions across which movement time is observed.

For each of the *depth*, *height* and *width* stimulus sets, there were 15 conditions, combining five object sizes with three amplitudes. The experiment was designed to ensure accurate estimates of average movement time, with the mean value per participant per condition calculated from nine observations. All available trials contributed to the calculation of means, because all reflected successful completion of the grasp in accordance with task instructions, as observed by the experimenter (RDM). Within a null-hypothesis significance testing framework, this design would be excessively well-powered, given the very high strength of the targeted relationship ($r^2 \geq .90$). However, it would be trivial to confirm merely that the relationship is significantly greater than zero. It is more relevant in the present context to be sure that the sample can support a sufficiently accurate estimation of the speed-accuracy trade-off. In evaluating the appropriate sample size for this purpose, we consider multiple regression with two predictors (two-factor model), because any sample adequate for this case will be more-than-adequate for the one-factor case (Fitts' equation).

Statistical treatments of this issue have been provided by Algina and Olejnik (2000) and Knofczynski & Mundfrom (2007). Algina & Olejnik (2000) focused on the accuracy of estimation of r^2 in multiple regression. Their Table 3 suggests that, for a population squared correlation of .90, with two predictors, a sample size of nine observations should estimate r^2 to within .15 of the population value 95% of the time; and 17 observations should estimate r^2 to within .10. Using a (conservative) assumption of a population squared correlation of .90, our 15 sampled conditions should allow us to estimate r^2 to comfortably within .15 of this value. This is a suitable pragmatic level of accuracy, implying that we should view any r^2 below .75 as a failure to fit a lawful speed-accuracy trade-off. Using a slightly different approach, Knofczynski & Mundfrom (2007, Table 1) recommended 15 observations as the minimum sample to achieve an 'excellent' level of prediction from multiple regression, given two predictor variables and an r^2 of .90. We thus have confidence that our design ensures replicable results. In addition, for any best-fitting model to be a candidate for an invariant law, it should not only predict group behaviour, but also that of each participant individually. Our best-fitting speed-accuracy trade-off should thus replicate ($r^2 > .75$) in each of our six participants, providing a robust check on its generality.

Following the modelling of movement time, additional more exploratory group analyses are conducted, to characterise major transport and grasp parameters. For each dependent variable, for the main *depth*, *height* and *width* stimulus sets, the mean value was extracted per participant per condition, and submitted to a repeated-measures ANOVA by reach amplitude and object size. A conventional alpha level of .05 was used, with Greenhouse-Geisser adjustments to the degrees of freedom if sphericity was violated. Assuming sphericity, these ANOVAs would be sensitive, with a power of .8, to a minimum effect size of partial $\eta^2 = .57$ for amplitude, and .43 for size. In practice, across stimulus sets and dependent measures, the Greenhouse-Geisser nonsphericity correction ranged down to .50 for amplitude and .26 for size, so that the minimum effect size detectable with .8 power ranged up to partial $\eta^2 = 0.71$ for amplitude and 0.7 for size.[2] These ANOVAs are thus reliably sensitive to very large effects only, but this is not a problem in the present context. First, each data point is the average of nine observations, so the precision of the data should be high. Second, the correlations between conditions were generally very high, which will magnify any consistent within-subjects effects (see footnote 2). Third, these ANOVAs are included to characterise the *major* kinematic changes that accompany speed-accuracy trade-offs; and relative insensitivity to less than wholly consistent effects is appropriate to this role. For the same reason, we concentrate on the main effects of amplitude and size, not exploring interactions beyond visual assessment.

---

[2] Sensitivity analyses were performed using G*Power v3.1.9.2 (Faul, Erdfelder, Lang, & Buchner, 2007; Faul, Erdfelder, Buchner, & Lang, 2009). G*Power can consider a maximum of one within-subjects factor at a time, so sensitivity analyses were performed separately for the effects of amplitude and size. However, we express the effect sizes as partial η^2 (rather than η^2) since, in practice, both factors will be present in the analysis. We selected the G*Power option to specify within-subjects effect sizes as in SPSS, the statistical package (v22) used for these ANOVAs. In SPSS, the calculation of η^2 (or partial η^2) takes account of the average correlation between levels of the within-subject factors. Across the three main object sets (depth, height, width), and the four kinematic variables (PS, TPS, TAPS, MGA) the median correlation we obtained between the three levels of amplitude was $r = .96$, range .92-.99; and between the five levels of size was $r = .98$, range, .78-1.0. (The correlations within the full matrix of the 15 conditions combining amplitude and size were similarly high, median $r = .94$, range: .80-.99.) Given such strong correlations across factor levels, it is reasonable to expect very large within-subjects effect sizes for any effects that are directionally consistent across subjects, as indeed was found (see Results).

Results

Our principal aim is to evaluate speed-accuracy trade-offs, predicting movement time (MT). Additional analyses more fully characterise the transport and grasp parameters of prehension.

Fitting Movement Time

Figure 2 shows mean movement time per *depth* and *height* condition, for the group and for each participant. In every participant, MT increased with reach amplitude, and decreased with object depth and height. For the *width* condition, group and individual data are shown in Figure 3a. The effect of width was directionally opposite to that of depth and height (movement duration was longer for wider objects), as predicted. Note that the influence of object width in Figure 3a is principally an elevation of movement time for the 90 mm object, with little consistent variation for widths below 40 mm. This could be because 90 mm is close to the largest graspable width for most people (see Bootsma et al., 1994). Alternatively, it might just be that the jump in width from 40 to 90 mm is greater than the entire range of widths below 40 mm.

It thus seems that our initial *width* set was sub-optimal, as there were no objects to track the effects of width over its range of main influence. The additional *width** set was created to fill in the missing range between 40 and 90 mm. Mean MT per *width** condition is shown in Figure 3b. The group plot suggests an approximately linear effect between (at least) 50 and 90 mm, but this varied somewhat across participants, with some in whom effects were visible across the range (e.g. Participants 1 and 5), and others in whom the relation was more scattered (e.g. Participant 3) or flat (Participant 6). The effects of width on MT thus seem to be more variable individually than those of depth or height.

The formal model-fitting began by fitting Fitts' equation to the average movement time across conditions, for the group mean results and for each participant individually. This equation has a single element (W) to represent the constraint on terminal accuracy, so to represent a three-dimensional target, simplifying choices are required. For the *depth* and *height* object sets, we followed previous authors by substituting the manipulated object dimension directly for W in the equation (Bootsma et al., 1994; Marteniuk et al., 1990; Zaal & Bootsma, 1993).[3] For the *width* object set, a prior adjustment was required, because the equation predicts an inverse relationship between width and movement time, but object width affects movement time in the opposite manner in prehension, with wider objects demanding greater accuracy of hand placement. To take account of this, we first subtracted the object width from 100, to represent the difference between the object width and a hypothetical maximum grip of 100 mm. The upper row of Figure 4 shows the results obtained fitting group mean movement time, by linear regression, using Fitts' equation for each object set. The clearly distinct effects of reaching amplitude and object dimension indicate that they are not appropriately combined into a single index of difficulty for prehension (cf. for aiming: MacKenzie & Graham, 1997; MacKenzie, Marteniuk, Dugas, Liske, & Eickmeier, 1987; Welford, 1968). The fits themselves were correspondingly poor, with r^2 never exceeding .80, and being generally much lower (see Table 1).

We thus followed Welford's recommendation of entering amplitude and size as two separate factors in our regressions. Welford's original two-factor model follows the equation: $MT = a + b \cdot \log_2 A + c \cdot \log_2 W$ (where a, b and c are constants). In the present study, we were relatively unconcerned with the effect of amplitude, which we sampled at three levels only (170, 320 and 470 mm), with no very short reaches. We thus assumed a logarithmic amplitude term, in line with Welford's equation and other prior research in the area (see Plamondon & Alimi, 1997); even if a linear term would have produced marginally better fits to our data, this could simply reflect the

[3] Because the non-manipulated dimensions were held constant at sizes unlikely to limit movement time, this is functionally analogous to MacKenzie and Buxton's (1992) strategy of using the smaller target dimension to compute the index of difficulty for rectangular aiming targets.

restricted range of amplitudes tested. Our primary interest was in the effect of object size, which we sampled at five levels for each of three dimensions, covering a representative range of graspable sizes. We evaluated a logarithmic size term, as in Welford's equation, and a linear size term (Figure 3 suggests that a linear effect is plausible for the *Width* dimension). Thus, for each object dimension, we compared the quality of fit using (1) MT = a + b•lgA + c•lgW with that obtained using (2) MT = a + b•lgA + c•W, substituting the manipulated dimension for W in each case.[4]

We operationalised the model comparison using the Akaike Information Criterion (AIC), a widely-used metric to compare the quality of statistical models (Akaike, 1998). All other things being equal, the model with the lower AIC parameter is considered the more likely, and the AIC difference them (ΔAIC) can be converted to a relative likelihood of the preferred model over the alternative [exp(ΔAIC/2)]. For height, model (1) was strongly preferred over (2), ΔAIC = 18.00 (relative likelihood 8085.98), with this difference being substantial in each of the six participants individually, ΔAIC 3.11 – 19.04 (relative likelihood 4.72-81951.81). For depth, the comparison was closer, but model (1) was preferred marginally for the group mean data, ΔAIC = 2.82 (relative likelihood 4.10), with three participants showing a clear advantage for model (1), ΔAIC = 3.89-10.81 (relative likelihood 7.00-222.70), and the other three showing negligible advantages for model (2), ΔAIC = 0.64-1.23 (relative likelihood 1.38-1.85). Overall, then, model (1) with a logarithmic size term was selected for the *depth* and *height* sets, matching Welford's equations. A different outcome was obtained for *width*, with strong evidence for model (2) over model (1), for the group mean data, ΔAIC = 12.19 (relative likelihood 443.23), and in each participant individually, ΔAIC = 1.13-11.84 (relative likelihood 1.76-372.01). Thus, the models selected were:

[4] Note that Fitts' original equation, and Welford's two-factor variation, used base 2 logarithms, owing to its origin within information theory, whereby the index of difficulty had the units of bits. Our equations do not include an index of difficulty interpreted in this way, so we use common logs (i.e. base 10), denoted by the notation lg.

For ***depth***: $MT = a + b \bullet \lg A + c \bullet lg(D)$

For ***height***: $MT = a + b \bullet \lg A + c \bullet lg(H)$

For ***width***: $MT = a + b \bullet \lg A + c \bullet W$

The selected two-factor model for each object dimension is plotted for the group mean data in the lower row of Figure 4, and Table 1 summarises the fit of this model for each dimension, for the group and for each participant individually.

Object dimension	Participant	ID (r^2)	two-factor (r^2)	coefficients (two-factor) a	b	c
Depth	Group	0.46	0.97	-296.68	341.18	-54.24
	p1	0.80	0.97	-272.17	367.96	-140.92
	p2	0.36	0.94	-212.20	292.09	-34.14
	p3	0.31	0.92	-341.76	345.80	-32.00
	p4	0.43	0.97	-379.52	421.69	-61.57
	p5	0.36	0.97	-368.98	311.21	-33.82
	p6	0.26	0.88	-205.46	308.35	-22.99
Height	Group	0.56	0.98	-272.60	345.59	-71.59
	p1	0.75	0.97	-165.15	299.88	-101.73
	p2	0.27	0.98	-383.45	358.77	-23.95
	p3	0.29	0.90	-226.79	297.95	-26.39
	p4	0.66	0.98	-254.98	399.59	-107.56
	p5	0.39	0.94	-387.95	337.85	-45.04
	p6	0.71	0.93	-217.31	379.47	-124.88
Width	Group	0.53	0.97	-306.07	297.27	0.65
	p1	0.75	0.92	-275.75	229.05	0.98
	p2	0.44	0.97	-301.77	297.54	0.54
	p3	0.53	0.97	-239.83	274.00	0.59
	p4	0.46	0.91	-268.53	332.34	0.60
	p5	0.48	0.95	-478.12	355.95	0.69
	p6	0.43	0.94	-272.40	294.74	0.50

Table 1. Model-fitting summary for each object dimension for the group and for each participant. ID (r^2) = fit using Fitts' index of difficulty; two-factor (r^2) = fit using preferred two-factor model; coefficients (two-factor) a = intercept, b = slope of amplitude effect, c= slope of size effect.

Additional analyses: transport component

Figure 5 shows group mean peak speed (PS) per condition for all object sets. The patterns contrast with those observed for MT (Figures 2-3). Whereas MT was modulated both by amplitude and object size (depth, height or width), PS was affected strongly by amplitude [*depth* set, $F(1.05, 5.25) = 150.70$, $p < .001$, partial $\eta^2 = .97$; *height* set, $F(1.04, 5.17) = 142.38$, $p < 0.001$, partial $\eta^2 = .97$; *width* set, $F(1.00, 5.02) = 103.34$, $p < 0.001$, partial $\eta^2 = .95$], but not by object size [the one significant outcome was for object *height*, $F(1.40, 7.02) = 7.49$, $p = .01$, partial $\eta^2 = .60$]. Variations in transport duration were thus achieved differently depending upon whether they were induced by a change in reach amplitude or a change in object size. In the former case, longer durations were associated with higher peak speeds; in the latter, they were not, so presumably were associated with changes in the *shape* of the velocity profile (cf. MacKenzie & Graham, 1997; MacKenzie et al., 1987).

This is confirmed by examining the duration of acceleration and deceleration phases of movement, before and after peak speed respectively. Figure 6 portrays the effects of amplitude and object size on time to peak speed (TPS) and time after peak speed (TAPS) for all object sets. Changes in amplitude induced changes in the acceleration *and* deceleration phases, whilst the effect of changing object size was restricted to the deceleration phase. Statistically, amplitude had significant main effects on TPS [*depth* set, $F(1.12, 5.58) = 29.60$, $p = 0.001$, partial $\eta^2 = .86$; *height* set, $F(1.31, 6.53) = 49.99$, $p < 0.001$, partial $\eta^2 = .91$; *width* set, $F(1.35, 6.76) = 19.54$, $p = 0.001$, partial $\eta^2 = .80$] and on TAPS [*depth* set, $F(1.28, 6.37) = 95.93$, $p < 0.001$, partial $\eta^2 = .95$; *height* set, $F(1.48, 7.40) = 103.10$, $p < 0.001$, partial $\eta^2 = .95$; *width* set, $F(1.28, 6.39) = 75.58$, $p < 0.001$, partial $\eta^2 = .94$]; but object size had significant effects on TAPS only [*depth* set, $F(1.22, 6.08) = 7.22$, $p = 0.03$, partial $\eta^2 = .59$; *height* set, $F(1.20, 5.99) = 13.57$, $p = 0.009$, partial $\eta^2 = .73$; *width* set, $F(2.50, 12.49) = 67.07$, $p < 0.001$, partial $\eta^2 = .93$; *width** set, $F(2.24, 11.21) = 11.08$, $p = 0.002$, partial $\eta^2 = .69$].

These patterns illustrate further why it is undesirable to combine changes in reach amplitude and object size into a unitary 'index of difficulty', as in Fitts' equation. Both factors influence MT, but in different ways, and for different reasons. Object size affects movement time because it changes the accuracy demands of grasping, and higher accuracy is achieved by selectively prolonging the deceleration phase of the movement. This positive skewing of the velocity profile affords more time in the terminal low-velocity phase for feedback-based adjustments. Though less dramatically, increases in reach amplitude also induce positive skewing of the velocity profile, as the deceleration phase is extended by more than is the acceleration phase (compare TPS and TAPS in Figure 6). This suggests that one consequence of increasing amplitude is to *effectively* raise the accuracy demands, because larger amplitude movements are inherently more variable (Harris & Wolpert, 1998); this raised accuracy demand is met by the *relatively* longer deceleration phase. However, increasing amplitude also raises movement time just because it requires the hand to travel further, which is achieved by scaling up the entire transport component, with extended acceleration and deceleration phases either side of a higher peak speed. Thus, whilst changes in movement time associated with object size reflect altered accuracy demands, those associated with reach amplitude additionally, and chiefly, reflect distance travelled.

Additional analyses: grasp component

Figure 7a shows group mean maximum grip aperture (MGA) per condition for all object sets. Object width of course had a powerful effect on MGA across its range, since this was the dimension that was grasped [*width* set, $F(1.17, 5.86) = 74.05$, $p < 0.001$, partial $\eta^2 = .94$; *width** set, $F(1.40, 6.98) = 64.26$, $p < 0.001$, partial $\eta^2 = .93$]. MGA was also modulated by depth and height despite the fact that neither depth nor height affected the grip size required to hold the object. As object size increased in either of these dimensions, MGA increased [*depth* set, $F(1.04, 5.20) = 6.30$, $p = .05$, partial $\eta^2 = .56$; *height* set, $F(1.15, 5.73) = 10.92$, $p = 0.01$, partial $\eta^2 = .69$]. Reach amplitude also affected MGA [*Depth* set: $F(1.47, 7.37) = 113.14$, $p < 0.001$, partial $\eta^2 = .96$; *Height* set: $F(1.67, 8.37) = 71.24$, $p < 0.001$, partial $\eta^2 = .93$. *Width* set: $F(1.80, 9.00) = 66.97$, $p < 0.001$, partial $\eta^2 = .93$], although it was similarly strictly irrelevant to the grip required to hold the object.

How can we explain the modulation of MGA by task parameters that, superficially at least, are irrelevant to the grip required? It is well known that grip aperture expands as the reach becomes more variable, for instance because of increases in speed (Bootsma et al., 1994; Jakobson & Goodale, 1991), removal of visual feedback (Wing et al., 1986) or increased visual uncertainty (Schlicht & Schrater, 2007). This may be relevant to the present data, because the increasing MGA with increasing depth and height (Figure 7a) occurs in parallel with a reduction in movement time (Figure 2). Reductions in movement time to take advantage of relaxed accuracy constraints in one dimension may induce correlated increases in variability in all dimensions, and a wider grip aperture provides the safety margin for this variability in the horizontal dimension. Increased variability of movement for larger amplitude movements (e.g. Harris & Wolpert, 1998) would similarly explain the increases in grip aperture with object distance.

The notion that grip aperture incorporates a safety margin for wrist positioning may in turn offer some insight into individual variations in the effects of object width upon MT (Figure 3). To illustrate, it is helpful to re-plot MGA values (Figure 7a) as safety margin (SM) values, where SM is the amount by which MGA exceeds the object width, calculated by subtracting object width from MGA (Figure 7b). For simplicity, we discuss medium amplitude reaches only (A=320 mm). For depth and height, as object size increases, so MT decreases, and MGA increases. At the largest values of depth and height (90 mm), the target objects have an identically large square contact surface on either side of a 20 mm graspable width. For all practical purposes, the accuracy constraints of these objects are as lenient as could be offered by any graspable cuboid, so we may assume that participants are moving at or close to the minimum possible duration for successful grasping at this amplitude (~450 ms on average). We can then ask how big a safety margin people give themselves to grasp successfully at this short duration. The data for the largest *depth* and *height* objects in Figure 7b indicate that this preferred safety margin is ~46 mm. If we then look at the width panels in Figure 7, we see that increases in MGA with object width are sufficient to keep the safety margin above this preferred value until object width passes ~50 mm, which is also the point at which width begins to produce noticeable increases in MT (Figure 3). Presumably, beyond this point, further increases in safety margin are more uncomfortable and/or inefficient than slowing the movement down. Individual differences in the precise point at which object width begins to limit MT might be determined by a variety of variables: psychological (e.g. motor skill, task strategy), biomechanical (e.g. finger-joint flexibility), and even anatomical (e.g. hand size).

Discussion

The present study establishes lawful relationships between each of the three dimensions of an object and the time taken to grasp it, as well as between reach amplitude and movement time. These relationships were clear at the group level, and in each participant individually. The directions of these relationships are predictable from a consideration of task demands: it takes longer to reach for more distant objects, and more time must be allowed to place the fingers on a contact surface that is smaller in either depth (parallel to the reach) or height (perpendicular to the reach). More time is taken to grasp wider objects, but only beyond a critical width that limits the safety margin built into the grip aperture: as the clearance between the fingers forming the grip aperture and the target is increasingly limited by target width, so movement times increase. This last result is reminiscent of that obtained by Fitts (1954) in a washer transfer task where the clearance between an annular washer and the peg onto which it was to be placed determined the movement time. These dimensional effects of object size are mediated by the constraints imposed on digit placement, which differ depending on the spatial relationship of each dimension with the formation of the grasp (see Figure 1). These relationships are therefore speed-accuracy trade-offs, though they do not conform to Fitts' law. Our data were well described by a two-factor model in which amplitude and size have distinct, additive effects on movement time (Welford, 1968). The relation was approximately logarithmic for object depth and height, and close to linear for width, underlining the distinct type of accuracy constraint imposed by the grasped dimension.

Object *width* had an intriguing influence on movement time, with little effect discernible below 40 mm width. Our supplementary manipulation, to focus on widths between 40-90 mm, showed a strong linear trend at the group level ($r^2 = .93$), though individually the fits ranged from good ($r^2 = .84$) to very poor ($r^2 = .12$). Individual differences in hand size and flexibility, and in the strategic adjustment of grip size to provide a safety margin for faster movements, may contribute to these variations in the effects of width. This may help explain why prior data on this relationship are somewhat inconsistent (Bootsma et al., 1994; Borchers et al., 2014; Jakobson & Goodale, 1991). The idea that grip aperture modulations create a safety margin for faster movements is well-established (e.g. Schlicht & Schrater, 2007; Wing et al., 1986), and it further offers an explanation for the unexpected effects of the non-grasped dimensions of the object (depth and height) on grip aperture in the present study. Specifically, as people move faster to take advantage of relaxed accuracy constraints in the depth or height dimensions, so they must open their hand wider to allow for the increased variability of horizontal wrist positioning that the faster movements will entail. A similar explanation would apply to the effects of amplitude upon MGA: larger amplitude movements are more variable (Harris & Wolpert, 1998), so a wider aperture is needed to allow more tolerance for wrist positioning, almost as if grip aperture were a valve for the transport component to let off steam. Not only are there *speed-accuracy* trade-offs in grasping, there are also striking *speed-aperture* trade-offs.

The present study was designed to clarify the speed-accuracy trade-offs in prehension, not to test between theoretical models of spatial aiming; but our results have implications for such models. One long-standing account of Fitts' law is that it emerges from a compromise between the durations of a primary transport movement and a feedback-based corrective sub-movement, given neuromotor noise that increases with the average velocity of the movement (Meyer et al., 1988). A more recent model gives even greater explanatory weight to signal-dependent neuromotor noise, with no necessary contribution from feedback-based corrections, arguing that Fitts' law emerges simply from the minimum movement duration for which the spread of movement endpoints falls within the target width (Harris & Wolpert, 1998). Several other models also reproduce Fitts' law type relationships, in which size and distance have equivalent effects on movement duration (e.g. Bullock & Grossberg, 1988; Crossman & Goodeve, 1983; Plamondon & Alimi, 1997). To the extent that such models lead *specifically* to a Fitts' law relationship, they will be unable, without ad-hoc adjustment, to explain the data presented here.

Our data are obviously consistent with Welford's (1968) theoretical position: that target distance and size place separate constraints upon movement time. This is supported by our analyses of the kinematic character of the transport movement. The increases in movement time with increasing distance were the result of an overall scaling up of the movement, with a higher peak speed and an extended time-course, but the increases associated with changes in object size were almost exclusively due to an extended deceleration phase, suggesting an important role for feedback-based correction (see also Bootsma et al., 1994; MacKenzie & Graham, 1997; MacKenzie et al., 1987). We suggest that object size imposes a 'pure' accuracy constraint, setting the tolerance for variability of movement endpoints, met largely by feedback-based control in the terminal stages of the movement. The distinct character of the kinematic changes associated with distance and size strengthen the theoretical basis for a two-factor model, and the pronounced effect of object size on the deceleration phase suggests a major role for closed-loop control of end-point variability in shaping the speed-accuracy trade-off, contrary to Harris & Wolpert's (1998) open-loop account.

In the context of prehension, it may be tempting to identify the separable factors of distance and size with the theoretical division of the prehension movement into transport and grasp components (Jeannerod, 1981, 1986). This looks like an obvious parallel, given that the target distance determines the scale of the overall transport, while the target size sets the accuracy constraints for the final grasp. However, there are reasons to doubt that it would be a useful basis for theoretical development. First, the two-factor model is not specific to prehension, but is a candidate for a more general speed-accuracy trade-off in spatially-constrained aiming, including in unidimensional tasks. As noted in the Introduction, a common observation is that movement times for different amplitudes fall on distinct straight lines when plotted against Fitts' index of difficulty.

The differences are often less extreme than those in Figure 4 of the present study, but they are usually clearly visible (e.g. Bainbridge & Sanders, 1972; Duarte & Latash, 2007; Gan & Hoffmann, 1988; Hoffmann & Sheikh, 1991; Jagacinski, Repperger, Moran, Ward, & Glass, 1980; Langolf et al., 1976; MacKenzie & Graham, 1997; MacKenzie et al., 1987; Sheridan, 1979; Welford, 1968).

Second, and consistent with the possibility of a general speed-accuracy trade-off, prehension itself can be considered as an elaborated form of simple aiming. The *digit control hypothesis*, proposed by Smeets & Brenner (1999), argues that transport and grasp parameters are not controlled explicitly during prehension, but are emergent properties of independent pointing movements of the finger(s) and thumb to opposing contact points on the object surface. In the original version of this model, the trajectories of the finger and thumb were each modelled by a minimum jerk criterion (Flash & Hogan, 1985), using some simple task constraints such as start and end positions, and angle of approach to surface (Smeets & Brenner, 1999). A more recent version of the model incorporates task objectives as well as constraints, for example the objective to avoid contact with non-target surfaces (Verheij et al, 2012). These digit-control models reproduce many empirical features of prehension, and its modulation with task variables, and they do so more parsimoniously than control schemes based upon the explicit control of transport and grasp (Borchers et al., 2014; Smeets & Brenner, 1999; Verheij et al., 2012, 2013; Verheij, Brenner, & Smeets, 2014). It will be of interest to see whether this model, perhaps adding the minimisation of movement time as a task objective, can reproduce the two-factor speed-accuracy trade-offs established by the present study.

Considering the consistency of these speed-accuracy trade-offs, it may seem surprising that they have not been clearly described before; at best, they have been seen indistinctly (Bootsma et al., 1994; Marteniuk et al., 1990; Zaal & Bootsma, 1993). A probable reason is that prior authors have modelled prehension movement time data using adaptations of Fitts' equation, whereas a two-factor model is more appropriate (Welford, 1968). We also argued that speed-accuracy trade-offs may have been masked by uncontrolled sources of variation, so to give ourselves the best chance of finding clear patterns, we designed a novel aerial grasping task. This task facilitated a straight path of approach, to align the grasp formation with the object's principal axes, and required the participant to fully control their own finger placement, rather than having the tabletop available as an end-stop. We constrained the grasp to a lateral finger-thumb pinch in order to hold the task constant, and we manipulated each object dimension independently. Nonetheless, using adaptations of Fitts' equation for each of the object sets, the prediction of movement time was poor ($.46 \leq r^2 \leq .56$ at the group level; $.26 \leq r^2 \leq .80$ for individual participants). This implies that uncontrolled sources of variation in standard grasping tasks do not sufficiently explain the empirical failure of Fitts' law. It is necessary to model the effects of reach amplitude and object size with distinct terms, and doing so allows for the near-perfect prediction of movement time ($r^2 \geq .97$ at the group level; $88 \leq r^2 \leq .98$ individually).

The lawful relationships we report were established via a classically reductionist experimental approach. This is a powerful strategy for isolating underlying regularities contributing to complex phenomena, but future work should explore the extent to which they are preserved or altered as the task is moved progressively away from our particular task towards the multifaceted complexity of the real world. One crucial point is that we isolated each object dimension for study, setting the other dimensions to values unlikely to limit movement time, which effectively allowed us to model the accuracy demands of the grasped cuboid as if it were a unidimensional target. Future studies should titrate the object's three dimensions against one another, to study how the accuracy demands interact. Perhaps a single size term representing the dimension most severely constraining accuracy can capture performance, as suggested for two-dimensional aiming (MacKenzie & Buxton, 1992). However, we must be careful to distinguish changes in the spatial parameters of the task (object distance, size and shape) from changes in the nature of the task itself, including: (i) grasping with or without supporting surfaces, which may alter the path of approach; (ii) grasping with a different intention (e.g. to hold or to lift the object), which may alter the desired precision of finger placement; (iii) grasping using different arrangements of digits (e.g. front-to-back or side-to-side, or with a power or precision grip). Such changes in the nature of the task will alter the task-specific parameters of the speed-accuracy trade-off, and may diminish the determining role of simple spatial factors. Such findings would not refute the speed-accuracy trade-offs described here, but would help us to understand how the minimisation of movement time is traded off against other behavioural goals in a wider range of real-world contexts.

References

Adam, J. J., Mol, R., Pratt, J., & Fischer, M. H. (2006). Moving Farther but Faster: An Exception to Fitts's Law. Psychological Science, 17(9), 794–798.

Akaike, H. (1998). Information Theory and an Extension of the Maximum Likelihood Principle (pp. 199–213). Springer, New York, NY.

Algina, J., & Olejnik, S. (2000). Determining Sample Size for Accurate Estimation of the Squared Multiple Correlation Coefficient. Multivariate Behavioral Research, 35(1), 119–137.

Bainbridge, L., & Sanders, M. (1972). The generality of Fitts's Law. Journal of Experimental Psychology, 96(1), 130–133.

Beamish, D., & Bhatti, S. (2006). Fifty years later: a neurodynamic explanation of Fitts' law. Journal of The Royal Society Interface, 3, 649–654.

Beggs, W., & Howarth, C. (1972). The movement of the hand towards a target. The Quarterly Journal of Experimental Psychology, 24(4), 448–453.

Bohan, M., Longstaff, M. G., Van Gemmert, A. W. A., Rand, M. K., & Stelmach, G. E. (2003). Differential Effects of Target Height and Width on 2D Pointing Movement Duration and Kinematics. Motor Control, 7(3), 278–289.

Bootsma, R. J., Marteniuk, R. G., MacKenzie, C. L., & Zaal, F. T. J. M. (1994). The speed-accuracy trade-off in manual prehension: effects of movement amplitude, object size and object width on kinematic characteristics. Experimental Brain Research, 98(3), 535–541.

Borchers, S., Verheij, R., & Smeets, J. (2014). The influence of object height on maximum grip aperture in empirical and modeled data. Journal of Experimental Psychology: Human Perception and Performance, 40(2), 889–896.

Bullock, D., & Grossberg, S. (1988). Neural dynamics of planned arm movements: emergent invariants and speed-accuracy properties during trajectory formation. Psychological Reviewew, 95(1), 49–90.

Cousineau, D. (2005). Confidence intervals in within-subject designs: A simpler solution to Loftus and Masson's method. Tutorials in Quantitative Methods for Psychology, 1(1), 42–45.

Crossman, E. R. F. W., & Goodeve, P. J. (1983). Feedback control of hand-movement and Fitts' law. The Quarterly Journal of Experimental Psychology Section A, 35(2), 251–278.

Duarte, M., & Latash, M. L. (2007). Effects of postural task requirements on the speed–accuracy trade-off. Experimental Brain Research, 180(3), 457–467.

Faul, F., Erdfelder, E., Buchner, A., & Lang, A.-G. (2009). Statistical power analyses using G*Power 3.1: tests for correlation and regression analyses. Behavior Research Methods, 41(4), 1149–1160.

Faul, F., Erdfelder, E., Lang, A., & Buchner, A. (2007). G* power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. Behavior Research Methods, 39(2), 175–191.

Feldman, A., & Levin, M. (2009). The equilibrium-point hypothesis–past, present and future. Advances in Experimental Medicine and Biology, (629), 699–726.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. Journal of Experimental Psychology, 47(6), 381–391.

Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. Journal of Experimental Psychology, 67(2), 103–112.

Flash, T., & Hogan, N. (1985). The coordination of arm movements: an experimentally confirmed mathematical model. Journal of Neuroscience, 5(7), 1688–1703.

Gan, K., & Hoffmann, E. R. (1988). Geometrical conditions for ballistic and visually controlled movements. Ergonomics, 31(5), 829–839.

Girgenrath, M., Bock, O., & Jüngling, S. (2004). Validity of the speed-accuracy tradeoff for prehension movements. Experimental Brain Research, 158(4), 415–420.

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. Nature, 394(6695), 780–784.

Hermann, U., & Soechting, J. F. (1997). Neuronal and muscular correlates consistent with Plamondon's theory: velocity coding and temporal activation patterns. Behavioral and Brain Sciences, 20(2), 311–312.

Hoffmann, E. R. (1995). Effect of transported mass and constant force on times for ballistic and visually-controlled movements. Ergonomics, 38(5), 951–970.

Hoffmann, E. R., Drury, C. G., & Romanowski, C. J. (2011). Performance in one-, two- and three-dimensional terminal aiming tasks. Ergonomics, 54(12), 1175–1185.

Hoffmann, E. R., & Sheikh, I. H. (1991). Finger Width Corrections in Fitts' Law: Implications for Speed-Accuracy Research. Journal of Motor Behavior, 23(4), 259–262.

Jagacinski, R. J., Repperger, D. W., Moran, M. S., Ward, S. L., & Glass, B. (1980). Fitts' law and the microstructure of rapid discrete movements. Journal of Experimental Psychology: Human Perception and Performance, 6(2), 309–320.

Jakobson, L. S. S., & Goodale, M. A. (1991). Factors affecting higher-order movement planning: a kinematic analysis of human prehension. Experimental Brain Research, 86(1), 199–208.

Jeannerod, M. (1981). Specialized channels for cognitive responses. Cognition, 10(1–3), 135–137.

Jeannerod, M. (1986). The formation of finger grip during prehension. A cortically mediated visuomotor pattern. Behavioural Brain Research, 19(2), 99–116.

Jüngling, S., Bock, O., & Girgenrath, M. (2002). Speed-accuracy trade-off of grasping movements during microgravity. Aviation, Space, and Environmental Medicine, 73(5), 430–435.

Knofczynski, G. T., & Mundfrom, D. (2007). Sample Sizes When Using Multiple Linear Regression for Prediction. Educational and Psychological Measurement, 68(3), 431–442.

Langolf, G., Chaffin, D., & Foulke, J. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. Journal of Motor Behavior, 8(2), 113–128.

MacKenzie, C., & Graham, E. (1997). Separating A and W effects: Pointing to targets on computer displays. Behavioral and Brain Sciences, 20(2), 316–318.

MacKenzie, C. L., Marteniuk, R. G., Dugas, C., Liske, D., & Eickmeier, B. (1987). Three-dimensional movement trajectories in Fitts' task: Implications for control. The Quarterly Journal of Experimental Psychology Section A, 39(4), 629–647.

MacKenzie, I., & Buxton, W. (1992). Extending Fitts' law to two-dimensional tasks. In Proceedings of the SIGCHI conference onon Human factors in computing systems (pp. 219–226).

Marteniuk, R. G., Leavitt, J. L., MacKenzie, C. L., & Athenes, S. (1990). Functional relationships between grasp and transport components in a prehension task. Human Movement Science, 9(2), 149–176.

Meyer, D., Abrams, R., Kornblum, S., & Wright, C. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. Psychological Review, 95(3), 340–370.

Morey, R. D. (2008). Confidence Intervals from Normalized Data: A correction to Cousineau (2005). Tutorials in Quantitative Methods for Psychology, 4(2), 61–64.

Murata, A., & Iwase, H. (2001). Extending Fitts' law to a three-dimensional pointing task. Human Movement Science, 20(6), 791–805.

Newell, K. M., Hoshizaki, L. E. F., Carlton, M. J., & Halbert, J. A. (1979). Movement Time and Velocity as Determinants of Movement Timing Accuracy. Journal of Motor Behavior, 11(1), 49–58.

Plamondon, R., & Alimi, A. M. (1997). Speed/accuracy trade-offs in target-directed movements. Behavioral and Brain Sciences, 20(2), 279–349.

Saltzman, E., & Kelso, J. A. (1987). Skilled actions: A task-dynamic approach. Psychological Review, 94(1), 84–106.

Schlicht, E., & Schrater, P. (2007). Effects of visual uncertainty on grasping movements. Experimental Brain Research, 182(1), 47-57.

Schmidt, R. A. (1975). A schema theory of discrete motor skill learning. Psychological Review, 82(4), 225–260.

Schmidt, R. A., & Lee, T. D. (2011). Motor control and learning: a behavioral emphasis (5th ed.). Champaign, IL: Human Kinetics.

Schmidt, R. A., Zelaznik, H., Hawkins, B., Frank, J., & Quinn, J. T. J. (1979). Motor-output variability: A theory for the accuracy of rapid motor acts. Psychological Review, 86(5), 415–451.

Sheridan, M. R. (1979). A Reappraisal of Fitts' Law. Journal of Motor Behavior, 11(3), 179–188.

Smeets, J., & Brenner, E. (1999). A new view on grasping. Motor Control, 3(3), 237–271.

Todorov, E. (2004). Optimality principles in sensorimotor control. Nature Neuroscience, 7(9), 907–915.

Tresilian, J. R. (2012). Sensorimotor control and learning. New York: Palgrave Macmillan.

Tresilian, J. R., & Stelmach, G. E. (1997). Common organization for unimanual and bimanual reach-to-grasp tasks. Experimental Brain Research, 115(2), 283–299.

Verheij, R., Brenner, E., & Smeets, J. B. J. (2012). Grasping kinematics from the perspective of the individual digits: A modelling study. PLoS ONE, 7(3), e33150.

Verheij, R., Brenner, E., & Smeets, J. B. J. (2013). Why are the digits' paths curved vertically in human grasping movements? Experimental Brain Research, 224(1), 59–68.

Verheij, R., Brenner, E., & Smeets, J. B. J. (2014). The influence of target object shape on maximum grip aperture in human grasping movements. Experimental Brain Research, 232(11), 3569–3578.

Welford, A. T. (1968). Fundamentals of skill. London: Methuen.

Wing, A. M., Turton, A., & Fraser, C. (1986). Grasp size and accuracy of approach in reaching.

Journal of Motor Behavior, 18(3), 245–260.

Wu, J., Yang, J., & Honda, T. (2010). Fitts' law holds for pointing movements under conditions of restricted visual feedback. Human Movement Science, 29(6), 882–892.

Zaal, F., & Bootsma, R. (1993). Accuracy demands in natural prehension. Human Movement Science, 12(3), 339–345.

Zelaznik, H. N., Mone, S., McCabe, G. P., & Thaman, C. (1988). Role of temporal and spatial precision in determining the nature of the speed-accuracy trade-off in aimed-hand movements. Journal of Experimental Psychology: Human Perception and Performance, 14(2), 221–230.

Figure 1. Schematic diagram of an 'aerial' grasp. The object, mounted on a thin metal rod, was grasped side-to-side, across its width, between finger and thumb. The hand start position (not shown) was from mid-air, directly in line with the centre of the object.

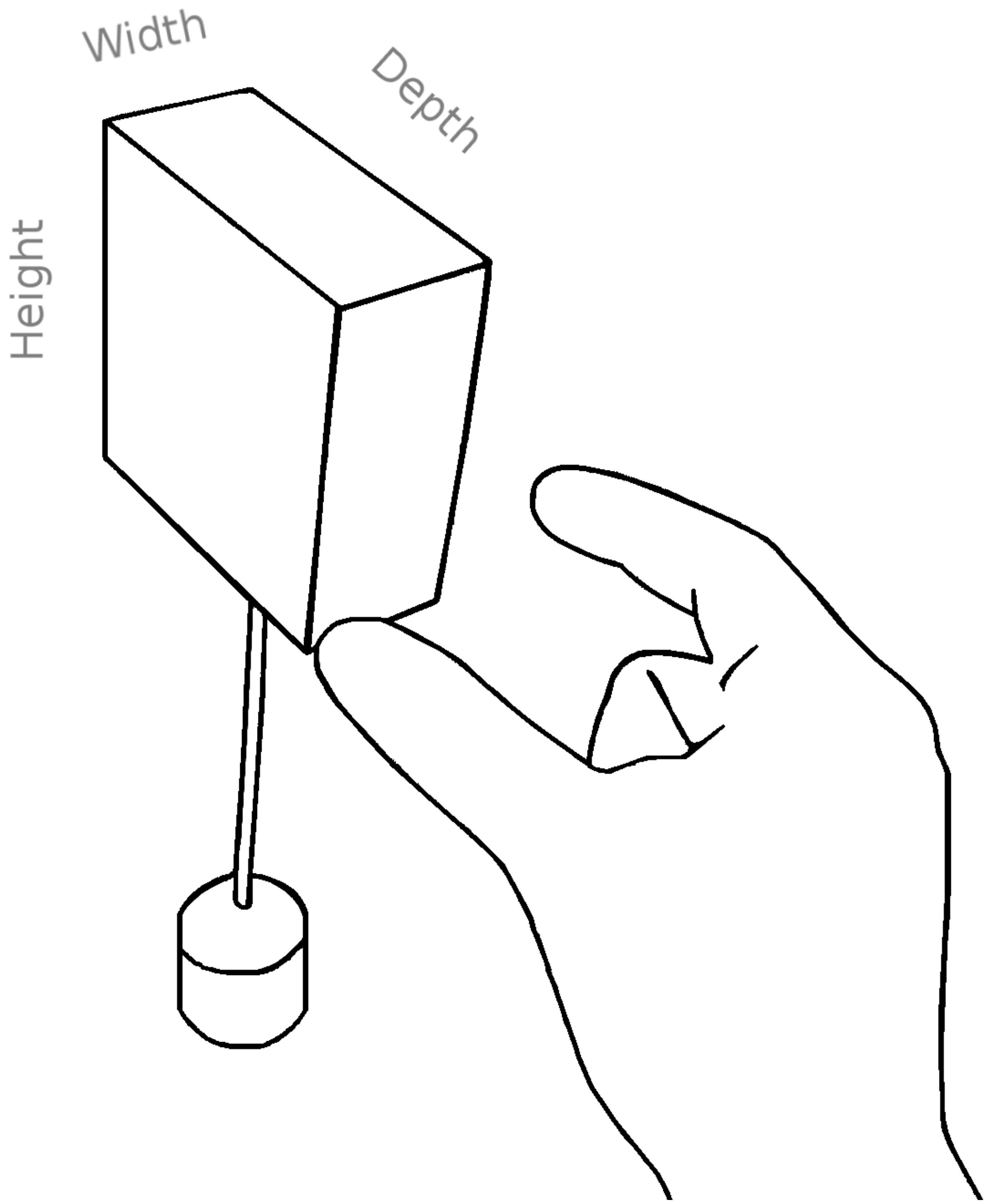

Figure 2. (a) The effect of object depth and movement amplitude (A) on movement time, for the group and for each participant. **(b)** The effect of object height and movement amplitude (A) on movement time, for the group and for each participant. In all plots, error bars show 95% confidence intervals around the mean; for the group plots, these are calculated for within-subjects designs (Cousineau, 2005, with correction by Morey, 2008). Note the logarithmic spacing on the x-axes.

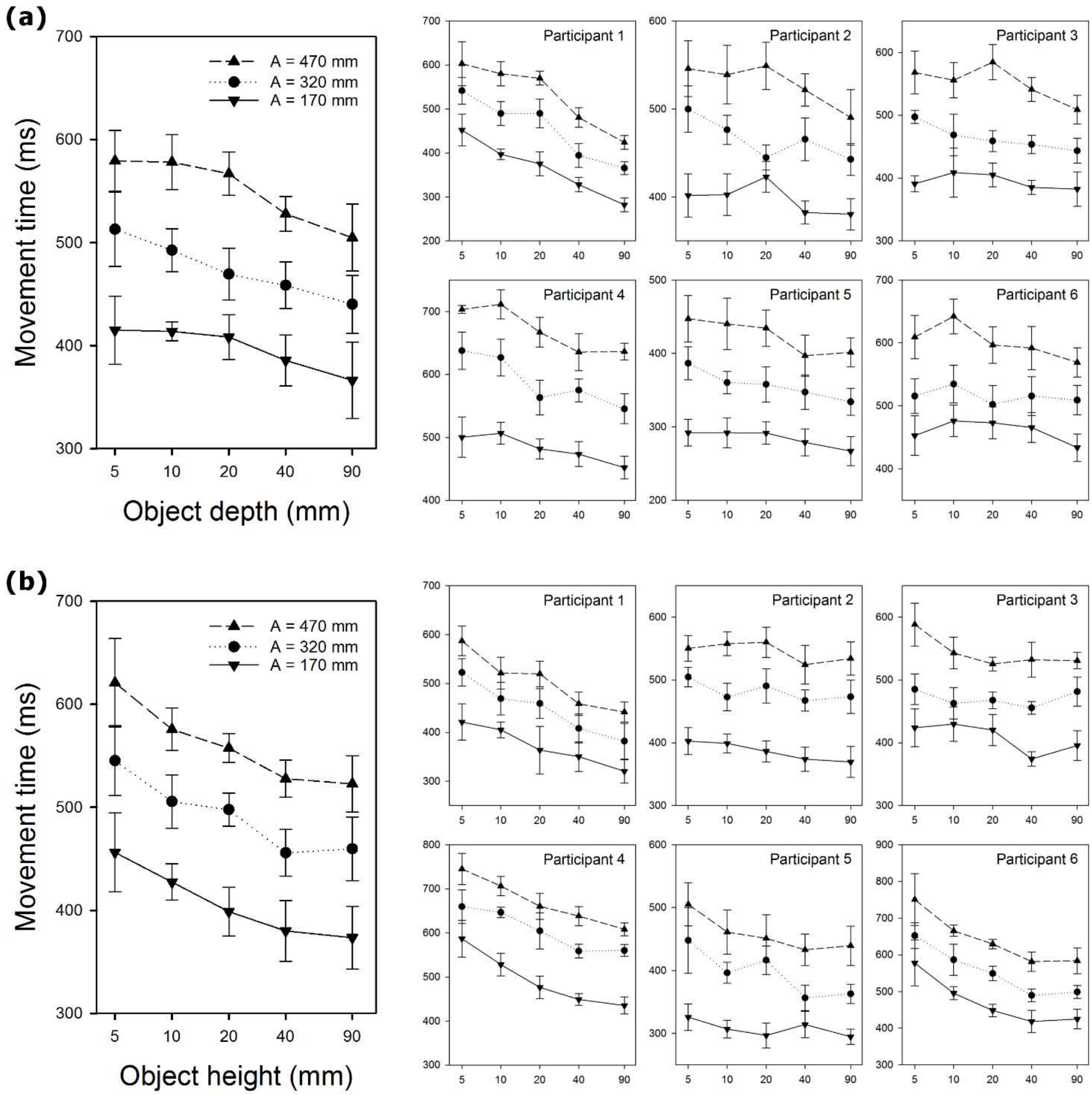

Figure 3. (a) The effect of object width (original stimulus set) and movement amplitude (A), for the group and for each participant. **(b)** The effect of object width* (additional stimulus set) on movement time, at a movement amplitude of 320 mm, for the group and for each participant. In all plots, error bars show 95% confidence intervals around the mean; for the group plots, these are calculated for within-subjects designs (Cousineau, 2005, with correction by Morey, 2008).

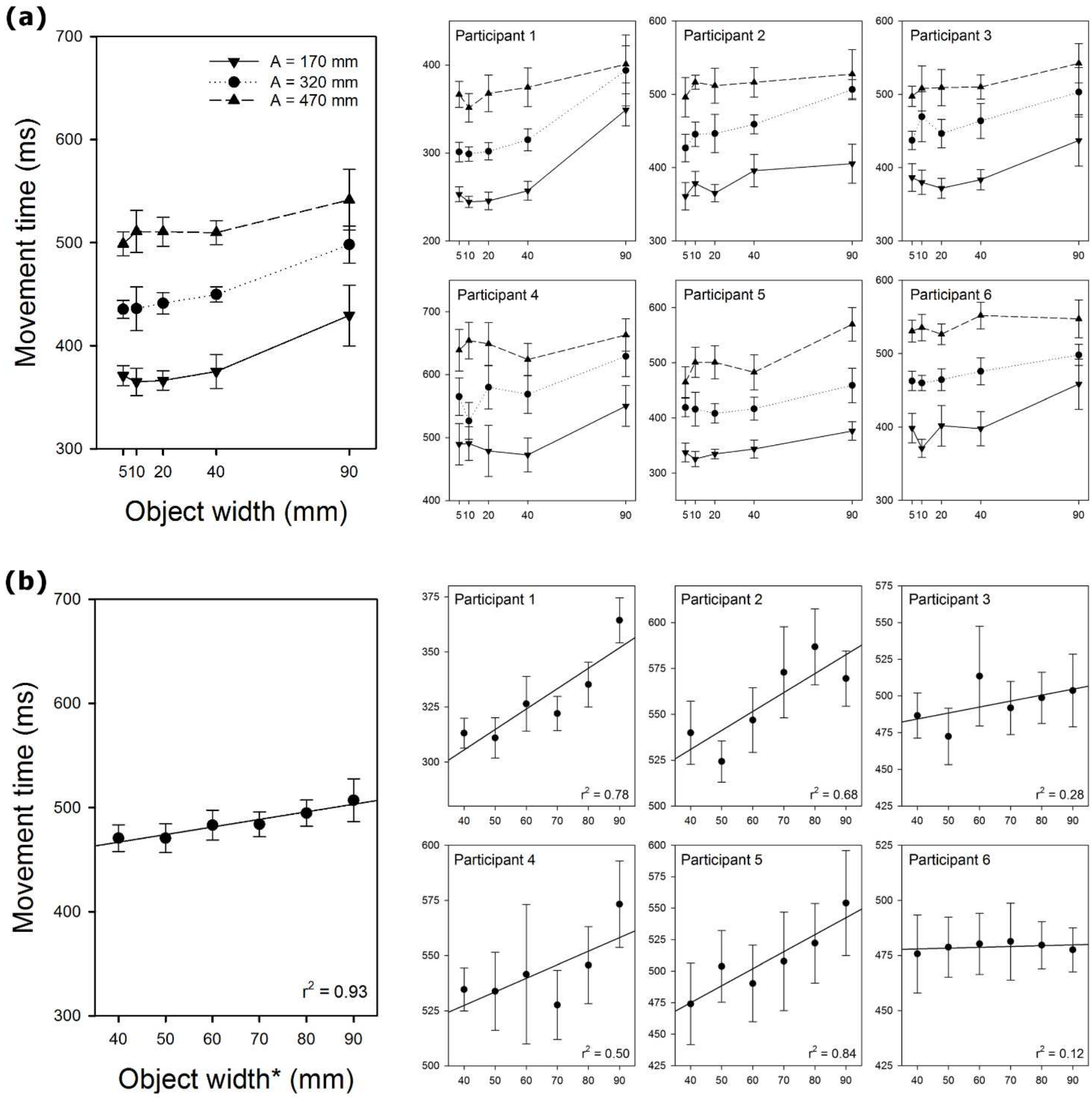

Figure 4. Empirical prediction of prehension movement time. The upper row shows the prediction of movement time from a simple adaptation of Fitts' equation, for manipulations of object depth (D), height (H) or width (W), and movement amplitude (A). There are clearly distinct effects of size and amplitude, indicated by solid and dashed lines respectively. The lower row shows the prediction by the best two factor model. The open circles on the rightmost plots show superimposed data for the additional width* stimulus set, plotted against the predictive equations derived from the main width stimulus set. The coefficients (a, b and c) are assumed to be constant for a given individual (or group) performing a given task; and lg indicates the common logarithm (base 10). Note that the group mean observed movement times are replotted from the major panels of Figures 2 and 3, which additionally show the corresponding confidence intervals.

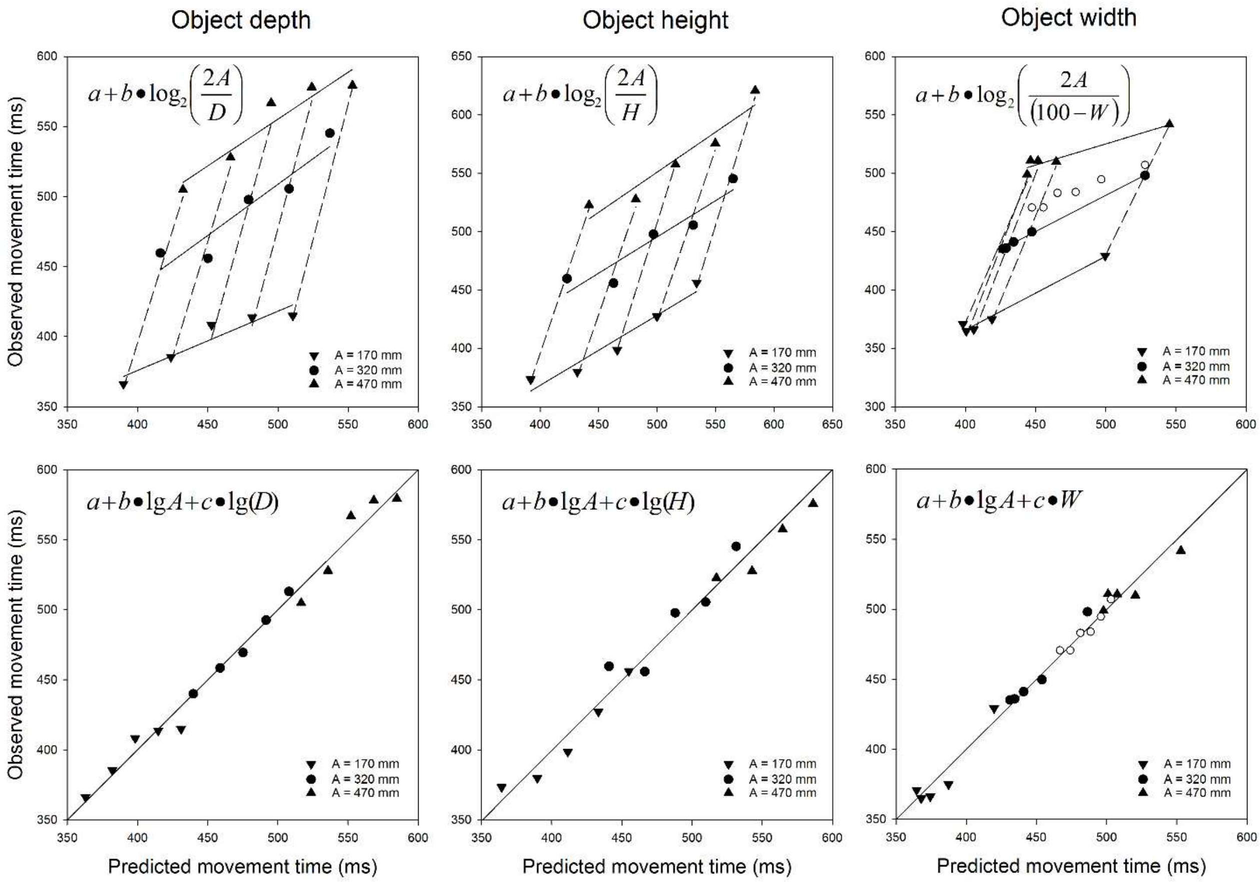

Figure 5. The effect of object size (depth, height and width) and movement amplitude (A) on peak speed of the transport component, for the group. The open circles on the rightmost plot show superimposed data for the additional width* stimulus set. In all plots, error bars show 95% confidence intervals around the mean, calculated for within-subjects designs (Cousineau, 2005, with correction by Morey, 2008).

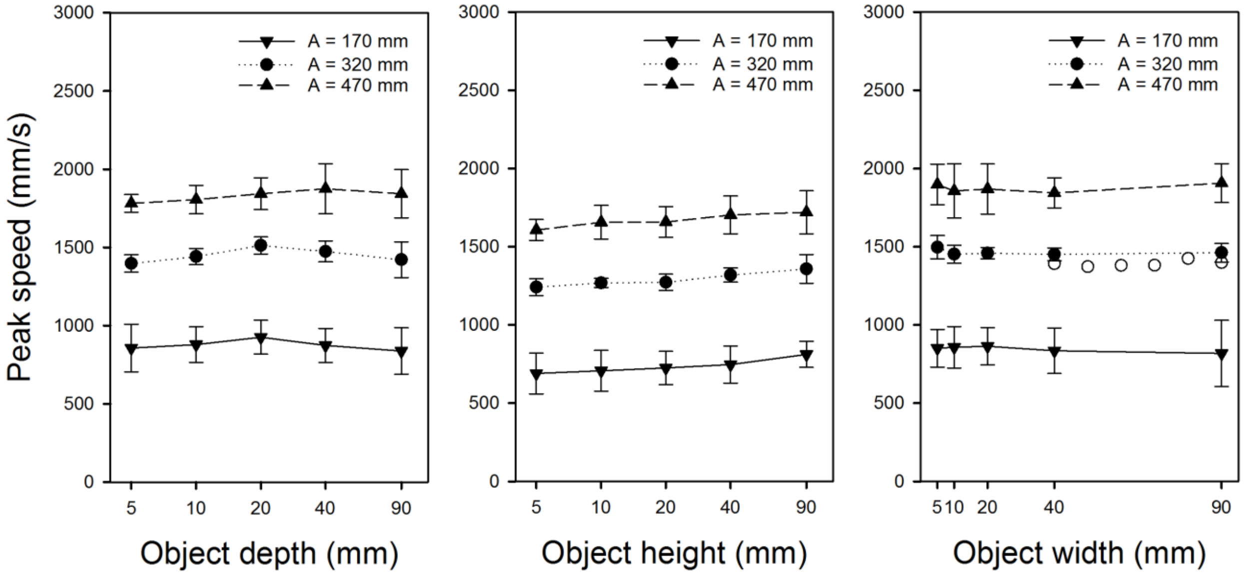

Figure 6. The effect of object size (depth, height and width) and movement amplitude (A) on the shape of the velocity profile of transport, for the group: **(a)** in terms of Time to Peak Speed (TPS) and **(b)** in terms of Time After Peak Speed (TAPS). The open circles on the rightmost plots show superimposed data for the additional width* stimulus set. In all plots, error bars show 95% confidence intervals around the mean, calculated for within-subjects designs (Cousineau, 2005, with correction by Morey, 2008).

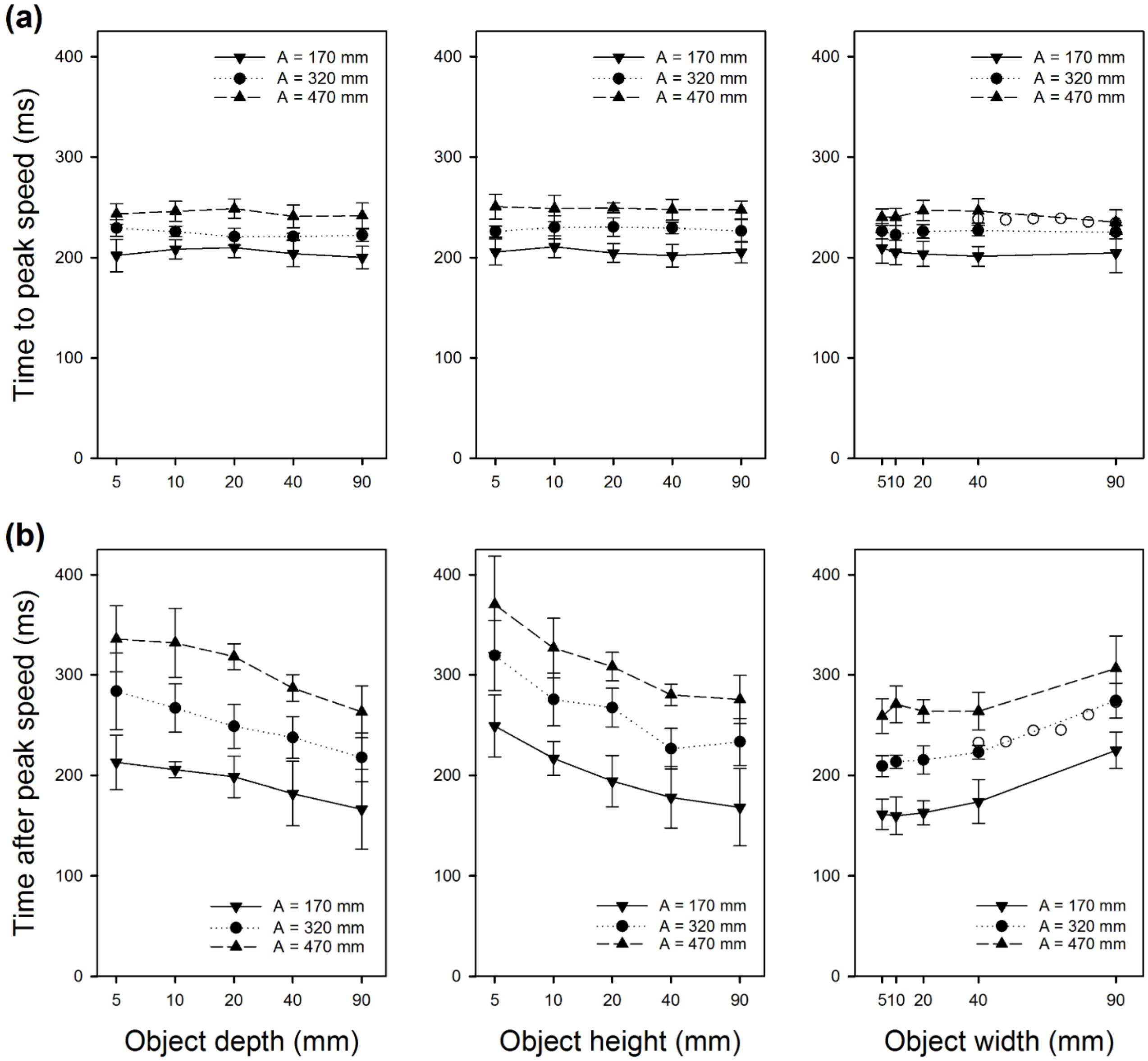

Figure 7. (a) The effect of object size (depth, height and width) and movement amplitude (A) on maximum grip aperture, for the group. **(b)** The data from panel (a) have been replotted, subtracting object width from the maximum grip aperture, to show the safety margin of the grip as it approaches the object. The open circles on the rightmost plots show superimposed data for the additional width* stimulus set. In all plots, error bars show 95% confidence intervals around the mean, calculated for within-subjects designs (Cousineau, 2005, with correction by Morey, 2008).