Testing the concurrent validity of a naturalistic upper extremity reaching task

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Compliance with Ethical Standards

Research involving Human Participants

Informed consent

ABSTRACT

Point-to-point reaching has been widely used to study upper extremity motor control. We have been developing a naturalistic reaching task that adds tool manipulation and object transport to this established paradigm. The purpose of this study was to determine the concurrent validity of a naturalistic reaching task in a sample of healthy adults. This task was compared to the criterion measure of standard point-to-point reaching. Twenty-eight adults performed unconstrained out-and-back movements in three different directions relative to constant start location along midline using their nondominant arm. In the naturalistic task, participants manipulated a tool to transport objects sequentially between physical targets anchored to the planar workspace. In the standard task, participants moved a digital cursor sequentially between virtual targets, veridical to the planar workspace. In both tasks, the primary measure of performance was trial time, which indicated the time to complete 15 reaches (five cycles of three reaches/target). Two other comparator tasks were also designed to test concurrent validity when components of the naturalistic task were added to the standard task. Spearman's rank correlation coefficients indicated minimal relationship between the naturalistic and standard tasks due to differences in progressive task difficulty. Accounting for this yielded a moderate linear relationship, indicating concurrent validity. The comparator tasks were also related to both the standard and naturalistic task. Thus, the principles of motor control and learning that have been established by the wealth of point-to-point reaching studies can still be applied to the naturalistic task to a certain extent.

Keywords: upper extremity; naturalistic; concurrent validity; reaching

INTRODUCTION

Reaching from point to point requires visual and proprioceptive information to be converted into coordinated motor patterns at the shoulder and elbow to smoothly move the hand through space, and as such, has become a classic sensorimotor paradigm for examining how the brain functions to plan and control movement (Scott 2000). Point-to-point reaching studies have been foundational in establishing our understanding of upper extremity motor control (Fitts, 1954; Flash and Hogan, 1985; Woodworth, 1899), neural encoding (Georgopoulos et al., 1982; Schwartz et al., 1988), motor development (Konczak and Dichgans, 1997; Lee and Newell, 2013), motor adaptation (Brashers-Krug et al., 1996; Krakauer et al., 2000; Smith et al., 2006), perception (Goodale and Milner 1992; Rosenbaum et al. 2011), and brain lateralization (Fisk and Goodale, 1988; Sainburg, 2014) in humans and animals (Fattori et al., 2010; Klein et al., 2012; Martin and Ghez, 1988). In addition to its contributions to basic neural mechanisms, the paradigm of targeted reaching has uncovered detailed deficits in a variety of clinical neurological populations, such as stroke (Beer et al., 2004; Dukelow et al., 2012; Velicki et al., 2000; Zackowski et al., 2004), Parkinson's Disease (Kelly and Bastian, 2005; Semrau et al., 2014), Alzheimer's Disease (Ghilardi et al., 1999; Tippett and Sergio, 2006; Verheij et al., 2012), and multiple sclerosis (Casadio et al., 2008; Solaro et al., 2007).

Why then might we want to develop a more naturalistic motor task? In general, strengthening a methodology's functional and predictive relationships with various real world settings (i.e. ecological validity) (Sbordone, 1996, p. 16) can increase its effectiveness, practicality, and utility (Roy-Byrne et al., 2003; Saturni et al., 2014). Although single-joint reaching studies described and established critical correlations between neural processes and motor behavior (Brown and Cooke, 1981, 1984; Fetz et al., 1989; Polit and Bizzi, 1979), multijoint reaching tasks further extended our knowledge of both overlapping and distinct features of motor control and planning between the two paradigms (Goodman and Gottlieb, 1995; Gribble and Ostry, 1999). As such, the 1) removal of mechanical constraints, 2) inclusion of multijoint coordination and motor redundancy, 3) ability to move in three dimensions rather than a single plane, and 4) increase in task complexity all subsequently improved the methodology's functional relationship to real-world movements (Desmurget et al., 1997; Johnson, 2006; Scheidt and Rymer, 2000). We have recently begun developing and testing a more naturalistic reaching task (Schaefer et al., 2013; Schaefer et al., 2015; Schaefer, 2015) that builds directly on the design of previous 'center-out' reaching tasks as well as functional upper extremity assessments (Jebsen et al., 1969) as an effort to further tackle the 'vital concept' of ecological validity (Spooner and Pachana, 2006, p. 327). We operationally define 'naturalistic' as requiring purposeful, multi-step actions (e.g. Hartmann et al., 2005) rather than involving only one movement component (e.g. only reaching), which is consistent with other naturalistic approaches to motor control (for review see Ingram and Wolpert, 2011) and rehabilitation (Reinkensmeyer, 2010; Stewart et al., 2007). Before assuming, however, that the control mechanisms for reaching that are recruited in this naturalistic task are similar to those derived from point-to-point reaching tasks, we must first test whether there is a close relationship between performance on the two tasks (Mislevy and Rupp, 2010).

Thus, the purpose of this study was to test the concurrent validity of a naturalistic motor task against the standard paradigm of point-to-point reaching, which served as our criterion measure. We hypothesized that across participants, performance on the naturalistic task would show a significant relationship with that of the standard reaching task, e.g. participants who took longer to complete the naturalistic task would also take longer to complete the standard task. This would serve as evidence of concurrent validity. We also hypothesized, however, that reaching tasks involving only individual components of the naturalistic task would be more related to the standard task, compared to the whole naturalistic task itself.

METHODS

Participants

Twenty-nine adults (17 female, 12 male) were recruited from the local community to participate in this study. Mean ± SD age was 20.5 ± 2.2 years. Based on preliminary trial time data from 5 participants, a priori power calculations indicated that at least 22 participants were needed to provide 80% power with a α-level of .05 for measuring significant performance differences between the naturalistic (experimental) and standard (control) reaching tasks. Exclusion criteria included 1) one or more self-reported neurological conditions (e.g. history of concussion); 2) acute or chronic musculoskeletal conditions that could affect upper extremity motor function; and 3) mixed-handedness. Hand dominance was determined using a modified Edinburgh Handedness Questionnaire (Oldfield, 1971). Only participants with a laterality quotient of ≥80% ("strongly right-handed") or ≤-80% ("strongly left-handed) were included in this study. One participant reported mixed-handedness (laterality quotient = 0) and was therefore excluded from the analysis. Of the remaining 28 participants, 27 were right-handed. All aspects of this study were conducted in accordance with the Declaration of Helsinki, and all procedures were carried out with prior approval by the University's Institutional Review Board. Informed consent was obtained from all individual participants included in the study prior to enrolling.

Experimental setup and kinematic analysis

Three-dimensional (3D) position data were collected with an electromagnetic six degree-of-freedom (6-DOF) movement recording system (Flock of Birds®, Ascension Technology Corp, Shelburne, VT). This system was integrated into Motion Monitor software (Innovative Sports Training, Chicago, IL) for data collection and exporting. A Flock of Birds sensor was placed either 1) on the dorsal portion of the distal phalanx of the nondominant index finger (secured to the fingernail, sensor Model 800), or 2) at the center of mass on the underside of a conventional plastic spoon (sensor Model 200) and held in the nondominant hand. Given the nondominant hand's tendency to be more variable in numerous aspects of reaching relative to the dominant hand (e.g. McManus et al., 1986; Mickevičienė et al., 2015), we used nondominant hand performance for the purposes of this study to minimize threats to validity and maximize the generalizable boundaries of the construct domain (Messick, 1995; Cook and Campbell, 1979). Kinematic data were collected at 100 Hz and filtered at 8 Hz using a second-order Butterworth filter for exporting. Resultant velocity from sensor data using standard rigid body methodology (Wu et al., 2005), and custom-written software in MATLAB (The MathWorks, Natick, MA) was used for subsequent analyses.

Experimental tasks

General methods and variables

In all tasks, participants were instructed to move "as quickly yet as accurately as possible" between a constant 2 cm x 2 cm start location and one of three 2 cm x 2 cm targets. All tasks were also unconstrained. The three targets were oriented 45° clockwise, 0°, or 45° counter-clockwise from the start location at a radial distance of 25.5 cm, with the middle target centered along the participants' midline. These directions were selected in order to systematically vary the effective inertial load at the hand, as well as the coordination patterns across the upper extremity joints, as participants reached to the different targets (Hogan, 1985; Sainburg and Kalakanis, 2000). The target order remained the same across all tasks (left-center-right) and was repeated five times for a total 15 reaches.

The start location was 15 cm in front of the seated participants. Figure 1 summarizes the tasks' setups with respect to each other.

For all tasks, the primary measure of performance was trial time, calculated as the time to complete 15 reaches. Trial start was defined as the timepoint when the three-dimensional resultant velocity of the endpoint (hand) sensor exceeded 0.03 m/s within the start location; trial end was defined as the timepoint when the three-dimensional resultant velocity of the endpoint (hand) sensor fell below 0.03 m/s at the final target. Additional measures of performance included cumulative hand distance, individual reach interval, peak reach (resultant) velocity, and initial movement direction. Cumulative hand distance was computed as the accumulated 3-D distance traveled by the sensor from trial start to end (Brodie et al., 2014), thereby serving as a proxy for the "straightness" or linearity of the handpath given that higher values indicate more distance traveled (Schaefer et al. 2009). Individual reach interval (IRI) was computed as the elapsed time between movement reversals at the target locations. For this measure, we defined movement reversal as the sensor's maximum y-position (anterior-posterior) within the target boundaries. The elapsed time between each movement reversal was calculated as the individual reach interval. Peak hand velocity was computed as the maximum 3D resultant velocity between the start and target locations during each reach. Initial movement direction was measured in degrees in a right-arm coordinate system, and was calculated as the xy-projection angle of the sensor's position at peak velocity (~250-350 ms) relative to 0° (positive x-axis, see Fig. 1). As such, we extracted 15 values of peak velocity and movement direction per trial, allowing us to analyze each target direction (left vs. center vs. right) separately.

Naturalistic reaching task

We operationally defined 'naturalistic' in this study as requiring purposeful, multi-step actions (Giovannetti et al., 2002; Hartmann et al., 2005; Schwartz et al., 1998). In light of this, we have developed a task that is designed to simulate several motor behavioral features of feeding, and have used it recently to measure motor learning (Cherry et al., 2014; Schaefer and Lang, 2012; Schaefer et al., 2013; Schaefer et al., 2015). This task requires repetitive multijoint coordination and has been adapted from the simulated feeding subtest of a clinical assessment (Jebsen et al., 1969) that objectively assesses hand function for activities of daily living.

In this task, participants sat at a table in front of a board (60.5 cm x 40.0 cm) with three target cups secured around the start cup (all 9.5 cm diameter, 6 cm tall) as described in "*General methods and variables*." Thirty objects (kidney beans, raw) were contained within the start location, and participants were instructed to use the instrumented spoon to acquire two beans at a time and transport them from the start cup to the correct target cup with the nondominant hand, starting with the leftmost target. Kidney beans were used in compliance with the Jebsen Hand Function test materials (Jebsen et al., 1969; see above). Participants were instructed to not initiate their reach to the target location until they had acquired two beans on the spoon. No beans were dropped during the transport phase; thus, 100% of the reaches in the naturalistic task were successful. Once the participants had transferred the objects to the target, they returned to the start location for the next reach. The trial was terminated once the final reach had been completed (i.e. no remaining objects in the start location), and the kinematic data were auto-saved to the collection computer.

Standard point-to-point reaching task

In this task, participants sat at a table facing a vertical 101.6 x 76.2 cm rear-projection screen (Da-Lite® Holo Screen #21491, Warsaw, IN). At the start of each trial, two items were projected onto the screen: the constant start location, (see "*General methods and variables*"), and a 1 cm "X" cursor that represented the 2-D finger (sensor) position along the tabletop. This virtual reality display was designed and calibrated to ensure that the projection was veridical in distance. Full visual feedback of the nondominant arm was provided throughout each trial, and the cursor was continuously visible throughout the experiment. Once the participants had held the cursor in the start location at a resultant velocity <0.001 m/s for more than 0.02 seconds, the leftmost target appeared and the start location was extinguished. This prompted participants to use their nondominant hand to move the cursor to the target. The target was then extinguished once the cursor landed within target and resultant velocity dropped below 0.03 m/s. The start location then reappeared, prompting the participant to move the cursor back to the start. The subsequent targets appeared in a similar fashion, as described above. The trial was terminated once the final reach had been completed, and the kinematic data were auto-saved to the collection computer (Dell Precision T3500). Because this task only required participants to reach from point-to-point, it served as the criterion measure to which all other tasks were compared for concurrent validity.

Titration of tool and object components into the standard task

To account for the added components of holding a tool and transporting objects relative to the standard task, we also had two other tasks that involved these different components. In both cases, the methods were identical to the standard task, but instead of reaching from point to point with their index finger, participants reached while grasping the instrumented spoon by itself (tool only), or the spoon holding two beans (tool + object). These were assumed to be systematically less complex than the naturalistic task, yet more complex than the standard task, thereby putatively 'filling the gap' between the naturalistic and standard tasks. In these cases, the cursor was driven by the position of the sensor placed on the spoon, rather than on the fingertip.

Data collection and analysis

Participants first completed five familiarization reaches (1/3 of a complete trial) between the start location and the center target. All participants then completed five trials of each task (naturalistic, standard, tool, and tool + object) in randomized blocks. Trial times, cumulative hand distances, IRIs, and peak hand velocities were averaged across trials per participant for statistical analysis. Aside from the instructions to use the nondominant hand and to move as quickly and as accurately to the targets, no specified or constrained patterns of upper extremity kinematics were required, such as moving in a straight line or minimizing changes in acceleration. Instead, participants used self-selected movement strategies to complete each task.

Statistical analysis

Statistical analyses were performed using JMP Statistics for Macintosh, Version 10 (SAS Institute Inc., Cary, NC) at a α-level of .05. Assumptions of normality were tested with Shapiro–Wilk tests. In the event of non-normality, Steel-Dwass (multiple comparisons) or Steel (control comparison) tests were used to compare variables between levels instead of analyses of variance (ANOVAs). To test for concurrent validity, mean values of performance variables were computed for each participant for each task (naturalistic, tool only, and tool + object) and were then compared against the criterion measure (standard task) to test the strength of association. Pearson product-moment correlation coefficients were calculated by the pairwise deletion method to examine relationships between tasks, and served as the validity coefficient (Mislevy and Rupp, 2010). In nonparametric cases, Spearman's rank correlation coefficients (ρ) were instead used as the validity coefficient. Validity coefficients greater than 0.59 were considered to be strong, between 0.30–0.59 were moderate, and below 0.30 were weak (Cohen, 1988).

Based on the results from the above analyses, we ran secondary tests for additional data interpretation. Because each trial was comprised of 15 reaches to three different targets, each trial was broken down into five cycles of reaches to the left, center, and right targets, thereby collapsing across movement directions per cycle to account for kinematic variations due to inertial anisotropies (Gordon et al., 1994). We then tested whether mean IRIs in the second through fifth cycles of the trial were significantly different from the first cycle using control comparisons, thereby probing for any changes in task difficulty (easier or harder) as the trial progressed. Each reaching task was analyzed separately. All figures were generated in using JMP Statistics for Macintosh (see above) and formatted using Adobe Illustrator CC 2014 (Adobe Systems Inc., San Jose, CA).

RESULTS

Characterizing task performance

Representative data from a single participant for each task are shown in Figure 2. Figure 2a shows a 2-D overhead view of the hand's trajectory from the start location to the three target locations over the course of the trial. Given the requirements for object manipulation and tool use at the start location in the naturalistic task, a close-up view of the hand trajectory is shown in Figure 2b, with the shaded circle indicating a 5 cm radius around the start location. Resultant hand velocity profiles are shown in Figure 2c, illustrating the repetitive reaches comprising each trial. In the naturalistic task, the hand trajectory was more extensive relative to the other three, particularly around the start location.

Assumptions of normality were violated for trial time (Shapiro-Wilk W=0.92; $p<.0001$), cumulative hand distance (W=0.72; $p<.0001$), and peak velocity (W=0.83, $p<.0001$) across tasks. Steel-Dwass tests indicated that trial time and cumulative hand distance for the naturalistic task were significantly longer compared to all other tasks ($p<.0001$), whereas the remaining tasks were similar on both measures (all $p>.11$). Peak velocities did not vary significantly between target directions (left vs. center vs. right) (all $p>.18$). Thus, when collapsing across directions, velocity was lowest for the naturalistic task compared to the standard ($p<.0001$) and tool only tasks ($p<.001$), yet it was comparable with the tool + object task ($p=.98$). This supported that our experimental design effectively titrated in the different components, such that more overlap in task requirements yielded more similar velocities. Mean performance is shown for each task in Figure 3.

Likewise, the longer trial times for the naturalistic task were consistent with its assumed increased complexity relative to the other tasks, particularly at the start location where participants were required to use a tool to acquire the objects for transport. Given the increased area traveled by the hand near the start location (see Fig. 2b), we tested whether how long participants took to complete a trial was related to how far their hand traveled over the course of a trial. Spearman rank order coefficients indicated a significant monotonic relationship between trial time and cumulative hand distance for the naturalistic task only ($\rho=.61$; $p<.001$) and not for any other task ($\rho=-.03$ to $.25$; $p=.19$ to $.84$). Furthermore, we observed that the durations of the naturalistic task trials were extended substantially by reaches performed later in the trial (Fig. 2c), suggesting that the task became increasingly more difficult as the trial progressed. This is consistent with the task design, as the number of objects in the start location decreased as participants transported them to the target locations during the trial. As the trial progressed, participants spent more time at the start location, attempting (i.e. 'rooting around') to acquire the object with the tool for transport in the instructed fashion and thereby increasing the cumulative distance traveled by the hand and amount of time taken to complete the trial. (Additional quantification of this behavior is detailed below in "*Accounting for task difficulty in concurrent validity*").

Testing the concurrent validity between tasks

Because of non-normality in our variables, nonparametric comparisons were required for testing whether measures from naturalistic task were consistent with the theoretical constructs being measured by the standard task. Although we expected concurrent validity between the naturalistic and standard tasks across participants, the pairwise comparison did not show a significant relationship (Table 1). That is, participants who took longer to complete the naturalistic task did not necessarily take longer to complete the standard task. Removing the task requirement of acquiring the objects for transport at the start location did, however, strengthen the relationship with the standard task, as seen with the tool only and the tool + object (Table 1). Similar associations between tasks were seen in pairwise comparisons of cumulative hand distance. Unlike the other variables, though, peak velocity for the naturalistic task was significantly related to that of the standard task, as were the other tasks (Table 1) with moderate to strong relationships.

Accounting for task difficulty in concurrent validity

As shown in Figure 2c, the time interval between reaches appeared to increase towards the last portion of the naturalistic task, as illustrated by longer durations in between maxima in the velocity profiles. Assumptions of normality (W=0.74; $p<.0001$) were again violated for mean individual reach intervals (IRIs) across the five cycles of reaches. Subsequent Steel tests revealed that mean IRIs for the third ($p<.01$), fourth ($p<.0001$), and fifth ($p<.0001$) cycles of the naturalistic task were significantly different from the first cycle. Only the second cycle was comparable to the first ($p=.38$). For all other tasks, mean IRIs were similar across cycles (all $p>.61$). This tendency for progressive difficulty, or lack thereof, is illustrated for each task in Figure 4. Longer IRIs indicated more time spent at the start location acquiring the objects for transport and, as in the case of the naturalistic task only, this was likely due to increased difficulty in doing so as fewer objects remained. The progressive difficulty within the naturalistic task was also evident in the initial movement direction (Fig. 5). This polar plot characterizes movement at the time of peak velocity; the direction of the vector indicates the direction of the hand's movement, and the length of the vector indicates the magnitude of peak velocity (see scale to right). All tasks showed consistent and appropriate movement directions (i.e. 135, 90, and 45° corresponding to the left, center, and right targets respectively) between cycles 1 and 5 except for the naturalistic task, which showed a progressive 'dedifferentiation' of initial direction such that the hand's position at peak velocity was less target-specific by cycle 5 relative to cycle 1.

To account for this difference in progressive task difficulty, we computed adjusted trial times based on the elapsed time to the end of cycle 2, just prior to the significant increase in IRI. Adjusted trial times were calculated for all tasks, and were tested for normality (W=0.98; $p=.18$). We then re-ran parametric pairwise comparisons for testing concurrent validity, and found that by accounting for changes in the naturalistic task's progressive difficulty, it now showed a significant and moderate linear relationship to the standard task (r=.52; $p<.01$) (Table 2). Moreover, the strengths of the relationship between the standard task and the other two tasks (tool and tool + object) were preserved in this adjustment, as indicated by the Pearson product-moment correlation coefficients in Table 2. Notably this adjustment did not affect the existing strength of the relationship between naturalistic and standard tasks for peak velocity when these values were compared only over the first two cycles (correlation coefficient = 0.33) rather than with the full five cycles as in Table 1.

DISCUSSION

The purpose of this study was to test the concurrent validity of a naturalistic motor task against the standard paradigm of point-to-point reaching. Somewhat in contrast to our initial hypothesis, we found that overall performance on the naturalistic task was not related to that of the standard task, indicating that participants who took longer to complete the naturalistic task did not necessarily take longer to complete the standard task. The amount of hand movement during the naturalistic task was also not related to the amount of hand movement in the standard task, as reflected in the cumulative hand distance. Only peak velocity was significantly related between the two tasks. Additional analysis indicated, however, that this lack of concurrent validity was partly attributed to the differences in the progressive within-trial difficulty for the naturalistic task and not for any other task. Accounting for this progressive difficulty improved the concurrent validity to a significant, moderate relationship in trial time. Thus, even though our naturalistic reaching task included non-reaching components and different task goals, it may still tap into constructs of interest shared by point-to-point reaching alone. Furthermore, we found that tasks into which individual movement components were titrated still showed strong concurrent validity with the standard reaching task.

Is no concurrent validity a bad thing?

Testing the concurrent validity of our recently developed task is critical for inferring overlap in the neural control of movement from established methods. In contrast to our initial hypothesis, however, we found minimal concurrent validity when comparing overall performance between the naturalistic and standard tasks. Although we identified a potential explanation for this lack of validity (i.e. differences in progressive difficulty), our secondary analyses that adjusted for this still reported 73% of unaccounted variance in trial time between the standard and naturalistic tasks ($r=.52$). This is not surprising, given the added task requirements such as tool use and manipulation, as well as object acquisition and transfer. These factors undoubtedly recruit additional, separate neural circuits within pre- and primary motor areas (for review see Castiello, 2005; Grafton et al., 1996), and certainly could have lengthened trial times relative to those without tool use or object acquisition (Gentilucci et al., 1991; Marteniuk et al., 1987) and when task difficulty is low (Leuthold and Schroter, 2011; Stewart et al., 2014; Winstein et al., 1997), which is consistent with our findings. Even when these non-reaching components of a goal-oriented, multistep task are factored out, the kinematics of its reach component alone can still be different to those of targeted reaching alone (Roy et al., 2000; Schaefer et al., 2012), and thereby involving different planning strategies

(Desmurget et al., 1997; Scheidt and Rymer, 2000). Given the neural and behavioral differences between the individual components of the tasks in this study, the significant moderate relationships for trial time and peak velocity between the naturalistic and standard tasks are noteworthy.

Data from the full-length trials (rather than those from the first two cycles of reaches only) suggest that different constructs comprise the different tasks. Although in this study we averaged across the five trials of each task to represent participants' overall performance, we have demonstrated in other studies that the naturalistic task can be used as a learning paradigm (Cherry et al., 2014; Schaefer and Lang, 2012; Schaefer et al., 2013; Schaefer et al., 2015), given the significant improvements in trial time with extended practice. Our data in this study suggest that this learning effect may be driven by changes in how quickly participants perform the 3^{rd}, 4^{th} and 5^{th} cycles of reaches across repetitive trials. To date, we had not tracked the hand's position throughout the 15 reaches of any given trial during a training session, and therefore had not been able to statistically identify where the most marked change in behavior (i.e. the practice effect) was occurring. Our interpretation of these data as indicating progressive difficulty was corroborated by how initial movement direction did (or did not) change from the first to fifth reach to each target. This more 'middle of the road' strategy for navigating different movement directions with the upper extremity as task difficulty increases has been described previously (Raw et al., 2012). As such, we now have a more detailed understanding of the naturalistic task's progressive difficulty, and how that difficulty may be attenuated through learning.

A second yet related explanation for the initial lack of concurrent validity may be that the naturalistic task recruits additional higher-order cognitive resources to a greater degree than does the standard task. We recently found a main effect of cognitive status on trial time in a sample of community-dwelling older adults when they performed the naturalistic task, such that those with mild cognitive impairment had significantly longer trial times than those without (Schaefer et al., 2015). Moreover, this effect persisted even after three days (>2000 reaches) of practice and one month of retention. One potential factor underlying this effect may be a differential reliance on executive function between the naturalistic and standard tasks, given the differences in task complexity. In both young and older adults, task complexity appears to account for the relationship between executive function and motor control, regardless of movement speed (Suchy and Kraybill 2007). That is, once the main effects of task (e.g. Fig. 3) and reach cycle (e.g. Fig. 4) are accounted for, the remaining variance in the naturalistic task not explained by the standard task may reflect different executive function requirements. For example, additional neural computations were necessary for participants to inhibit incorrect reaches (i.e. when the number of objects on the tool ≠ 2), not unlike other instances of upper extremity response inhibition measured behaviorally (Cantin et al., 2014; Hartman et al., 2010; Pratt et al., 2014).

Systematic comparison of movement components

When considering alternative paradigms for studying motor control and learning, one should consider directly monitoring and manipulating features of coordinated movement (Scott, 1999). Our tasks and variables were designed and selected with this consideration in mind. With respect to task design, we aimed to systematically add in, or 'titrate', components of the naturalistic task to the standard task, like reaching with the tool. We then compared performance across the different task 'titrations', as measured by the variables of trial time, cumulative hand distance, and peak velocity. Trial time reflected total movement time, which is an established proxy for task difficulty (Fitts, 1954; Sheridan, 1973) that is easily measureable (e.g. stopwatch) and can indicate learning even in clinical populations (Felix et al., 2012). Moreover, upper extremity movement time is related to the degree of white matter lesion (Wright et al., 2008), dementia (Bramell-Risberg et al., 2010; Yan and Dick, 2006), and lower extremity movement time (Michmizos et al., 2014). Its sensitivity and ease of measurability are two of many reasons why movement time is a key variable to measure, both experimentally and clinically. We also compared the accumulated distance traveled by the hand, which, when compared within a task itself, can quantify movement efficiency and intersegmental coordination (Brodie et al., 2014; Lang et al., 2005; Sainburg et al., 1995). With these measures, we found that the systematic addition of the naturalistic task's components into the standard task still maintained strong concurrent validity, and supports previous findings (Danion and Sarlegna, 2007). While more detailed kinematic analyses of the hand's path or individual limb segments/joints may have provided additional insights, we did not constrain movement patterns in order to afford self-selection in movement strategy and to allow the motion to be as naturalistic as possible (Reinkensmeyer, 2010); thus, the current study design likely yielded highly variable joint coordination patterns within and between participants (Adams et al., 2015; Bufton et al., 2014; Gates et al., 2012; Petuskey et al., 2007; Srinivasan and da Silva, 2011; Wisneski and Johnson, 2007) and multiple planning mechanisms (Desmurget et al., 1997; Scheidt and Rymer, 2000), which is consistent with goal-directed movement in daily life (Bailey et al., 2014). We therefore restricted our analyses to global temporal and spatial variables of the end effector in this study.

Acknowledging mono-operation bias and other limitations

Although we demonstrated moderate concurrent validity of the naturalistic task, we acknowledge the degree to which using single measures or variables can threaten validity (Cook and Campell, 1979). Because our measures of trial time (overall and adjusted) and peak velocity were continuous variables and objective in nature, the threat of mono-operation bias may have been minimized relative to more subjective, categorical measures of task difficulty (e.g. perceived exertion) or movement smoothness (Cozens and Bhakta, 2003; Levin, 1996; Slepian et al., 2013). We also acknowledge that concurrent validity was tested in a sample of healthy young adults, who displayed a low degree of inter-individual variability, particularly on the standard, tool, and tool + object tasks, as illustrated by the standard error bars in Figures 3 and 4. Nevertheless, further comparisons of other common measures of performance, such as inverse dynamic variables or joint angle derivatives, and in different populations (e.g. stroke, aging) will provide further insight into which constructs are or are not shared between tasks.

To summarize, we have preliminary evidence that, when accounting for progressive task difficulty, our naturalistic reaching task had moderate concurrent validity with the established criterion measure of point-to-point reaching. Thus, while the naturalistic task may recruit different neural mechanisms to perform its additional components, the principles of motor control and learning that have been established by the wealth of point-to-point reaching studies can still be applied to a certain extent. Our results therefore warrant further exploration of the naturalistic task in this study as a potential proxy for studying real-world upper extremity motor control.

TABLES

Table 1. Nonparametric pairwise comparisons for trial time, cumulative hand distance, and peak velocity

	Trial time		**Cumulative hand**		**Peak velocity**	
Task comparison	*ρ*	*p-value*	*ρ*	*p-value*	*ρ*	*p-value*
Standard vs. naturalistic	-0.10	0.63	-0.17	0.38	0.38	0.04*
Standard vs. tool	0.68	<.0001*	0.73	<.0001*	0.82	<.0001*
Standard vs. tool + object	0.72	<.0001*	0.75	<.0001*	0.72	<.0001*

*indicates significant relationship

Table 2. Parametric pairwise comparisons for adjusted trial time

Task comparison	*r*	*p-value*
Standard vs. naturalistic	0.52	0.005*
Standard vs. tool	0.64	0.0002*
Standard vs. tool + object	0.70	<.0001*

*indicates linear significant relationship

FIGURE CAPTIONS

Fig. 1 Top view of setup for each task, all shown with the corresponding effector (e.g. hand, spoon) moving to the left (135°) target. A more detailed graphical description about the naturalistic task can be found in Schaefer, 2015.

Fig. 2 Representative data for each task. a) Overhead view of the hand trajectory over the course of the trial. b) A close-up view of the hand trajectory around the start location. The shaded circle represents a 5-cm radius around the start location. c) Resultant hand velocity profiles for the corresponding trials.

Fig. 3 Mean ± SE trial time (top), cumulative hand distance (middle), and peak hand velocity (bottom) across participants for each task (Steel-Dwass **p<.001; ***p<.0001; ns = not significant relative to the naturalistic task).

Fig. 4 Mean ± SE individual reach interval (IRI) per cycle across participants for each task (Steel **p<.01; ***p<.0001).

Fig. 5 Polar plot of mean initial movement direction for reaches to the three different targets in cycles 1 (black) and 5 (gray). The direction of the vector indicates the direction of the hand's movement, and the length of the vector indicates the magnitude of peak velocity (see scale to right).

CONFLICT OF INTEREST: The authors declare that they have no conflict of interest.

ETHICAL APPROVAL: All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

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