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Research Report

The impact of left hemisphere stroke on force control with familiar and novel objects: Neuroanatomic substrates and relationship to apraxia

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ABSTRACT

Fingertip force scaling for lifting objects frequently occurs in anticipation of finger contact. An ongoing question concerns the types of memories that are used to inform predictive control. Object-specific information such as weight may be stored and retrieved when previously encountered objects are lifted again. Alternatively, visual size and shape cues may provide estimates of object density each time objects are encountered. We reasoned that differences in performance with familiar versus novel objects would provide support for the former possibility. Anticipatory force production with both familiar and novel objects was assessed in six left hemisphere stroke patients, two of whom exhibited deficient actions with familiar objects (ideomotor apraxia; IMA), along with five control subjects. In contrast to healthy controls and stroke participants without IMA, participants with IMA displayed poor anticipatory scaling with familiar objects. However, like the other groups, IMA participants learned to differentiate fingertip forces with repeated lifts of both familiar and novel objects. Finally, there was a significant correlation between damage to the inferior parietal and superior and middle temporal lobes and impaired anticipatory control for familiar objects. These data support the hypotheses that anticipatory control during lifts of familiar objects in IMA patients are based on object-specific memories and that the ventro-dorsal stream is involved in the long-term storage of internal models used for anticipatory scaling during object manipulation.

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Abbreviations: GF, grip force; LF, load force; IMA, ideomotor apraxia; LCVA, left cerebrovascular accident; GTS, percentage of total possible points on the Gesture to Sight of Objects apraxia measure; MTG, middle temporal gyrus; STG, superior temporal gyrus; TO, posterior temporo-occipital; IPL, inferior parietal lobe; IFG, inferior frontal gyrus; PM, premotor cortex; GFR, first peak grip force rate; LFR, first peak load force rate; GFR Order, percentage of correctly ordered GFRs; LFR Order, percentage of correctly ordered LFRs; GFR Distance, sum of GFR inter-item distance scores; LFR Distance, sum of LFR inter-item distance scores; Monofil, monofilament test; 2 pt, static 2-point discrimination in mm; GrStr, hand grip strength in lbs; Peg, grooved pegboard; MobergTtl, Moberg test total pickup time in s; MobergID, Moberg item identification time, in s; WAB AC, Western Aphasia Battery auditory comprehension subtest

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1. Introduction

Smooth and stable lifts of objects depend on memory representations that capture the relationship between physical properties of objects such as weight, the force requirements to lift the object, and the dynamics and mechanics of the sensorimotor system. Such memory representations, frequently characterized as "internal models," are used for anticipatory control during object lifts to prevent slippage and object deformation. By using predictions about object properties based on prior experience, anticipatory grip force (GF) and vertical load force (LF) enhance lift coordination (Flanagan and Tresilian, 1994; Wolpert and Flanagan, 2001; Kawato et al., 2003).

Anticipatory fingertip force deficits have been described in conjunction with several central nervous system disorders (Nowak et al., 2007b; Duff and Gordon, 2003) but to this point have not explicitly been identified in stroke populations (Nowak et al., 2007c). It is notable, however, that participants with a single-hemisphere stroke exhibit slow, inaccurate grips, and use excessive or variable grip force scaling bilaterally (Quaney et al., 2005; Blennerhassett et al., 2006). Such abnormalities might well be attributable, at least in part, to a deficit in anticipatory planning.

Most previous studies with adults post-stroke have solely assessed performance with novel geometric objects, such as cylinders or cubes (except see Gordon et al., 1993; Duff and Gordon, 2003), limiting their ecological relevance. Additionally, they have either failed to assess for the presence of ideomotor apraxia (IMA) (Nowak et al., 2003; Blennerhassett et al., 2006), or alternatively, have excluded participants who exhibited it (Raghavan et al., 2006; Quaney et al., 2005; Nowak et al., 2007c; Dafotakis et al., 2008; but see Li et al., 2007, for an exception). This appears to be a critical omission given that IMA, a disorder of complex object-related action observed in both the contralesional as well as ipsilesional hand, is a frequent consequence of stroke, particularly to the brain's left hemisphere. Individuals with IMA are deficient in anticipatory planning of hand posture and hand orientation (Buxbaum et al., 2005a) and rely upon visual feedback during action imitation (Jax et al., 2006) and in reaching to targets (Haaland et al., 1999). Therefore, IMA may reflect, at least in part, a deficit in storage or retrieval of internal models used for anticipatory control of object manipulation.

An additional relevant feature of IMA is a surprising disparity between actions to familiar versus novel objects in favor of the latter. For example, when tested with the ipsilesional hand, participants with IMA have difficulties recognizing and performing the correct hand postures for familiar objects, but perform normally on the same tasks with novel objects (Buxbaum et al., 2003), and are more impaired in imitation of the hand posture component of meaningful, as compared to meaningless, object-related actions (Buxbaum et al., 2007). This suggests that retrieval of stored representations may in some cases disrupt spatiomotor processing in IMA.

We postulated that the study of anticipatory force scaling during lifts of novel and familiar objects in participants with IMA would provide evidence relevant to the question of the nature of memory representations used for anticipatory force control. An ongoing question in the literature concerns the types of memories that are used for anticipatory control during object manipulation. There are several candidate theories. One possibility is that object-specific information such as weight is stored, either as part of an internal model or as an independent neural representation. Thus, when previously encountered objects are to be lifted again, the object-specific information is retrieved to scale the GF and LF needed for successful manipulation. Consistent with this possibility, healthy participants are able to scale load and grip forces to object weight on their first lift with familiar objects, but only after several lifts of a novel object when size-weight cues are absent (Gordon et al., 1993). An additional possibility is that visual size and shape cues allow for an estimation of object density every time an object is encountered (Mon-Williams and Murray, 2000; Quaney et al., 2003; Cole, 2008). There is evidence, for example, that predictive fingertip forces are adjusted when objects of constant density vary in size (Gordon et al., 1991). Thus, smaller objects are perceived as heavier than larger objects of the same weight, (the "size-weight illusion"), indicating that visual size cues are influential in initially estimating object weight until sensory feedback adjusts that estimate (Flanagan and Beltzner, 2000; Grandy and Westwood, 2006).

The influence of object-specific versus current visual information in anticipatory fingertip force scaling may be assessed by examining performance during lifts of familiar versus novel objects in healthy as well as in neurologic participants with suspected anticipatory control deficits. If different representations and processes contribute to lifting familiar as compared to novel objects (e.g., long-term versus short-term memories), then performance should differ for the two object types. Alternatively, if the same mechanisms and representations (such as the use of visual size cues to estimate density) are used for both object types, then performance should be parallel in the two cases.

The final goal of the study was to assess the left hemisphere lesion loci related to anticipatory control deficits during lifts of familiar and novel objects. In our previous work in individuals with IMA, we proposed that the behavioral distinction between hand postures associated with familiar versus unfamiliar objects is seated in a corresponding functional neuroanatomic distinction between two processing streams specialized for actions upon objects: a bilateral fronto-parietal system forming the dorso-dorsal stream, specialized for online control of visually-guided action based on object geometry (size, shape); and a left-lateralized inferior parietal lobe (IPL) and superior temporal gyrus (STG) system forming the ventro-dorsal stream, specialized for stored object-related actions (Buxbaum, 2001; Rizzolatti and Matelli, 2003; Buxbaum et al., 2005a; Frey, 2007). IMA patients with lesions to the "object use" system (but not "object grasp" system) have deficits not only in the production of object-related actions, but in their recognition as well, suggesting that a common representational deficit may underlie both impairments (Buxbaum et al., 2005b, 2007). In parallel, numerous functional neuroimaging studies have demonstrated left IPL and posterior STG activation when subjects observe or plan familiar tool-use movements (e.g., Johnson-Frey, 2004; Lewis, 2006; Creem-Regehr and Lee, 2005), as well as when they plan object-