Post-stroke object affordances: An EEG investigation.

Paula J. Rowe*, Corinna Haenschel, Nareg Khachatoorian and Kielan Yarrow

Cognitive Neuroscience Research Unit, Department of Psychology, City, University of London

* Author for correspondence:
Paula J. Rowe,
Rhind Building,
City, University of London,
Northampton Square,
London EC1V 0HB

Tel: +44 (0)20 7040 0161

Fax: +44 (0)20 7040 8580 Email: paula.rowe.1@city.ac.uk

Abstract

Rehabilitating upper limb function after stroke is a key therapeutic goal. In healthy brains, objects, especially tools, are said to cause automatic motoric ‘affordances’; affecting our preparation to handle objects. For example, the N2 event-related potential has been shown to correlate with the functional properties of objects in healthy adults during passive viewing. We posited that such an affordance effect might also be observed in chronic-stage stroke survivors. With either dominant or non-dominant hand forward, we presented three kinds of stimuli in stereoscopic depth; grasp objects affording a power-grip, pinch objects affording a thumb and forefinger precision-grip and an empty desk, affording no action. EEG data from 10 stroke survivors and 15 neurologically healthy subjects were analysed for the N1 and N2 ERP components. Both components revealed differences between the two object stimuli categories and the empty desk for both groups, suggesting the presence of affordance-related motor priming from around 100 to 370 ms after stimulus onset. Hence, we speculate that stroke survivors with loss of upper limb function may benefit from object presentation regimes designed to maximise motor priming when attempting movements with manipulable objects. However, further investigation would be necessary with acute stage patients, especially those diagnosed with apraxia.

Keywords

EEG; motor priming; upper limb deficits

1. Introduction

Approximately 795,000 people in the US have a new or recurrent stroke each year. The figure is around 100,000 for the UK. Stroke is also a leading cause of long-term disability (American Heart Association, 2017; The Stroke Association, 2018). Resulting long- and short-term disabilities vary greatly and among other deficits may include difficulties in swallowing and speech, hemiplegia, decreased function in upper or lower limbs, poor trunk control, visual difficulties, and fatigue. Here, the focus of our research is the loss of motor function in upper limb, particularly in the hand.

Position of lesion determines the resulting deficits. Not only are neurons lost at the site of injury but activity of surrounding cells is also reduced and damage often extends further because of changes in neurotransmitter transmission and blood flow. This may exacerbate the extent of motor deficits (Pekna et al., 2012). However, the human brain, particularly the cortex, has an ability to reorganize the structure and function of neural systems. This neuroplasticity is evident in all forms of learning where neuronal roles adapt to demand, e.g. learning a musical instrument. Neuroplasticity has been shown to be an essential factor in the recovery of upper limb function (Pekna et al, 2012, Wade et al., 2014).

Various rehabilitation methods are employed to aid neuronal reorganization to improve motor function after stroke. Gesture recognition and imitation requires a therapist to perform, or verbally request, a gesture, e.g., waving or making a ‘thumbs-up’ sign which the patient attempts to copy (Dovern et al., 2012; Pazzaglia et al., 2008). Improving the range of arm and hand mobility requires more complex approaches, such as pantomiming tool use, e.g., hammering a nail or scooping soup from a bowl. Since early work by Carr and Shepherd (1987), it has become common practice to offer tools and other manipulable objects as visual cues to aid recovery in therapeutic settings (e.g. Dovern et al., 2012; Pazzaglia et al., 2008; Wheaton et al., 2008). Including the physical objects for actual use, such as a soup bowl with spoon and the hammer and nails, may produce motor priming effects which better prepare patients for interaction with pairs of objects and can improve hand and arm coordination in patients (Randerath et al., 2011).

Here, we are particularly interested in how affordance-related brain activity may be affected after stroke with loss of hand function. The expression “affordance” was first introduced by JJ Gibson (1977, 1979/1986) who suggested that just by viewing an object we perceive one or more ways to interact with it; even when there is no intention to act, the intrinsic properties of an object will potentiate motor planning. Such properties may include shape, size, weight and even aesthetics (e.g. Righi, Orlando & Marzi, 2014). Along with any specific object familiarity we may have, such affordances play a part in our perception of objects and thus the motor priming that prepares us to handle or manipulate them. This has prompted many studies investigating action-perception aided by affordances (i.e. automatic priming of the motor system by viewed objects) in both human and non-human primates (e.g. Grèzes et al. 2003; Kühn et al., 2014; Murata et al. 1997; Rice et al. 2007; Tucker & Ellis 1998; Tucker & Ellis 2001; Valyear et al. 2007).

Interventions utilising naturally occurring “affordances” may assist neuroplasticity. However, the length of time during which such a visual cue has its optimum rehabilitative value to encourage meaningful movement has, thus far, received little attention. Ideally, we would need to know for how long the brain automatically processes the options an object affords before we consciously decide whether and how to act. Once defined in healthy adults, the duration of this initial motor priming could be refined for stroke patients. When the patient is unable to handle objects, he or she may benefit by their regular removal and re-introduction, with each such event triggering new affordance-related motor priming. As we outline below, evidence suggests that affordance-related brain activity in neurologically healthy individuals is transient, but this has not yet been generalised to stroke populations. Such knowledge would be valuable to inform the increasing use of virtual reality games as an intervention, where object-presentation rates can be refined to multiples of milliseconds.

A number of transcranial magnetic stimulation (TMS) experiments have attempted to address this temporal aspect of affordances, measuring motor priming in healthy participants when no physical response is required (Buccino et al. 2009; Cardellicchio et al. 2011; Makris et al. 2011; Franca et al. 2012; Makris et al. 2013). For example, single-pulse stimulation over left motor cortex facilitated larger motor evoked potentials (MEPs) at around 200ms after onset of stimuli when objects were presented with handles orientated towards the dominant right hand (Buccino et al. 2009). Similarly, sizes of MEPs were modulated for congruent hand muscles while participants viewed objects affording either a power or precision grip (Makris et al. 2011). In that study, electromyography (EMG) recordings from the first dorsal interosseous (FDI), required when making a pinch/precision grip, were significantly greater for observation of precision-grip affording objects compared to larger, power-grip objects, and vice versa for the abductor digiti minimi (ADM), a muscle involved in power gripping. Greatest facilitation occurred at around 300ms, but, interestingly, the affordance effect died away shortly thereafter as MEPs were not facilitated by a TMS pulse delivered at 600ms after stimulus onset.

Electroencephalographic (EEG) studies have also sought to measure the timing of affordances. Some have compared responses to pictures of tools with non-tools (Proverbio et al., 2011; Proverbio 2012) or pictures of objects compared to no object (Rowe et al., 2017). The N2 is the second negative event-related potential (ERP) component after stimulus onset and has been associated with motor facilitation (Allami et al. 2014). Proverbio et al. (2011) found significantly different activity between hemispheres. Greater anterior left hemispheric N2 negativity was found while viewing tools (including some objects associated with specific motor acts, such as a bicycle, stairs and a keyboard) compared to non-tools, i.e. objects not strictly associated with a motor act, e.g., a television, a carpet and a piece of pottery.

Our group have also investigated N2 activity when a manipulable object is observed We utilised images containing stereo depth cues, which are known to support accurate goal-directed visually guided reach-to-grasp actions (e.g. Melmoth & Grant 2006; Melmoth et al. 2007; Melmoth et al. 2009). Participants viewed the same 3D objects in two different sitting positions. Posture 1 was with their dominant (right) hand closer to the screen and Posture 2 was with the non-dominant (left) hand closer to the screen. Lateralized affordance bias from the objects themselves was eliminated as the objects were displayed with any handles presented centrally. A greater N2 ERP component emerged for object stimuli compared to the empty desk, but particularly when the object was close to the dominant hand. We also investigated purely visual discrimination as associated with the posterior N1 ERP component (Hopf et al., 2002; Mangun & Hillyard, 1991; Thorpe et al., 1996; Vogel & Luck, 2000). At the posterior PO3 and PO4 electrodes, the N1 ERP component had a very similar peak voltage at very similar latencies for all stimulus categories – whole hand grasp objects, pinch-grip objects and no object. However, anteriorly (at the F1 and F2 electrodes) this component did show differences in peak values between the stimulus categories.

These results suggest that the motoric N2, which is modulated by the presence/absence and functional significance of objects, may provide a sensitive measure regarding affordance-related motor priming. The anterior and posterior N1 ERP components also warrant further investigation. However, there are (at least) two outstanding questions which need to be addressed in order to move from the evidence showing affordances in healthy young participants towards a basic research justification for testing the potential of affordances to improve rehabilitative outcomes (e.g. a clinical trial). Firstly, we need to know whether motor priming still occurs in (undamaged) regions of the brains of stroke survivors when viewing images with depth cues through a stereoscopic viewer. Secondly, affordance-related activation appears to be transient, as evidenced by timing of TMS pulses for MEPs and the specific time-windows in which the N2 ERP component occurs. Therefore, we need to know how frequently to re-introduce objects in order to generate maximum motor priming within a time-limited therapeutic session.

In summary, here we ask:

1) Can ERP evidence of affordance-related motor priming be observed in chronic stage stroke survivors? To test this, we hypothesise differences in anterior N1/N2 components when viewing different categories of objects, and, ideally, a statistical interaction between this effect and factors that influence the functional relevance of the object, such as the participant’s posture.

2) If stroke survivors show motor priming, does the time-course of affordance-related brain activity observed by EEG differ relative to that found in age-matched control volunteers, and is it affected by the frequency of object presentation? To test this, we hypothesise statistical interactions between EEG effects indicative of automatic motor

priming (see 1, above) and additional factors, i.e. varying diagnosis (control vs. stroke survivor) and the rate at which stimuli are presented.

2. Materials and Methods

2.1. Participants

We recruited 10 stroke survivors (7 male, 3 female; mean age 65 years, SD 9 years) from an advertisement placed online through the charity, Different Strokes, and via stroke clubs affiliated to The Stroke Association. We did not conduct an a priori power analysis, but rather took a pragmatic approach, with recruitment ending when no further participants had been forthcoming via these routes for several months. Eight of these participants had left hemisphere lesion and two had right hemisphere lesion. Mean number of years post-stroke was 6.5 years (range 2 – 17 years). Participants had varying degrees of upper limb deficits, not specifically having a diagnosis of apraxia. Most were able to provide only limited information regarding site of lesion and type of stroke (see Table 1). Through local University of the Third Age groups we also recruited 15 similarly aged neurologically healthy control volunteers (4 male, 11 female; mean age 72 years, SD 5 years). Participants from both groups had normal or corrected-to-normal vision. All healthy control participants were right-handed and all stroke survivors had been right-handed prior to stroke, as verified by the Edinburgh Handedness Inventory, adapted from Oldfield (1971). Laterality Indices (LI) are shown in Table 2. For stroke survivors these are indicated prior to and post stroke.

Table 1. Stroke survivor participant ages, number of years post stroke, area of lesion and residual deficits. (FS = female stroke survivor, MS = male stroke survivor)

Participant	Age	Years post-stroke	Area of lesion	Residual neurological deficits
FS01	60	2	Left lenticulostriate ischemic stroke	Incoordination of right upper limb, and weakness in right lower and upper limbs
FS02	47	4	Left hemisphere	Aphasia, loss of function of right upper limb and weakness in right lower and upper limbs
FS03	67	11	Left hemisphere	Aphasia, loss of function of right upper limb and weakness in right lower and upper limbs
MS01	74	5	Left middle cerebral artery infarct, left internal carotid artery stenosis	Slightly reduced function in right upper limb.
MS02	72	17	Right hemisphere	Reduced flexion in left hand. Reduced flexion and extension of left elbow.
MS03	64	3	Right carotid artery blocked (left partially blocked)	Left lower limb weakness, non-functioning left upper limb
MS04	68	6	Left middle cerebral artery infarct	Aphasia, severely reduced hand function, weakness in right upper limb
MS05	71	4	Left basal ganglia haemorrhagic stroke	Right sided weakness, Returning activity to previously non-functioning right upper limb
MS06	75	3	Left partial anterior circulation stroke (PACS) CT scan showed a wedge-shaped infarct in left posterior frontal lobe	Aphasia, some loss of function and weakness in right upper limb
MS07	52	10	Left hemisphere	Aphasia, non-functioning right upper limb

Table 2. Participant ages, mini mental state exam (MMSE) scores, handedness lateral index (LI) and nine hole peg test (NHPT) timings. (N/C = not completed) (FC = female control volunteer, MC = male control volunteer, FS = female stroke survivor, MS = male stroke survivor)

Participant	**Age**	**MMSE score (/30)**	**LI for hand dominance**		**NHPT right hand (s)**	**NHPT left hand (s)**
FC01	68	30	100		22	29
FC02	68	30	100		20	23
FC03	73	30	100		27	21
FC04	79	28	76		25	30
FC05	77	30	72		32	22
FC06	66	30	100		19	21
FC07	75	29	100		26	30
FC08	65	30	82		22	22
FC09	79	30	100		26	25
FC10	69	29	100		24	27
FC11	80	29	100		24	22
MC01	74	30	50		19	18
MC02	68	30	64		24	20
MC03	69	30	100		24	23
MC04	71	30	29		19	18
FS01	60	26	100 prior	56 post-stroke	50	24
FS02	47	29	100 prior	-100 post-stroke	N/C	19
FS03	67	28	100 prior	-100 post-stroke	N/C	27
MS01	74	30	92 prior	43 post-stroke	56	25
MS02	72	29	100 prior	100 post-stroke	33	N/C
MS03	64	30	100 prior	100 post-stroke	29	N/C
MS04	68	29	100 prior	-100 post-stroke	N/C	27
MS05	71	28	100 prior	-100 post-stroke	N/C	28
MS06	75	29	76 prior	-100 post-stroke	N/C	25
MS07	52	27	100 prior	-100 post-stroke	N/C	30

All participants achieved ≥ 26 out of a total of 30 for a Mini-Mental State Examination (adapted from Folstein et al., 1975) and all attempted a nine-hole peg test (NHPT). Some stroke survivors were unable to complete the NHPT with their affected hand (see Table 2). No participants reported sensory or proprioception deficits. The study was approved by City, University of London Ethics Committee and participants gave written consent.

2.2. Stimuli

Initially, 3D photographs were taken of 40 objects positioned on a desk in such a way that no left or right laterality could be ascertained, i.e. either photographs of objects without handles or photographs of objects with the handle positioned centrally. Viewpoint and light source remained constant across photos. To establish object categories for the experiment, 20 independent assessors rated the photos on whether they would use a pinch grip or whole hand grasp to hold the objects. The assessors used three categories; “always use this grip/grasp”, “mostly use this grip/grasp”, or “just more likely to use this grip/grasp”. A separate independent group of 10 people then rated the objects from 0 to 2 on how familiar they were, with 2 being a very familiar object. Feedback from participants in our earlier study (Rowe et al., 2017) regarding visual clarity was also taken into account when a set of pictures was chosen from those with high assessor rankings which contained good exemplars of objects affording either a precision or power grip. These stimuli were used to construct three stimulus categories. The first category contained only a single stimulus (an empty desk) while the other two showed objects located on that desk. Object categories consisted of one picture of each of three objects, which would normally be held in either a precision grip (pinch objects: a wax crayon, a pencil sharpener and a wrapped sweet) or a power grip (grasp objects: a hairbrush, a trowel and a box).

2.3. Design and Procedure

Participants were seated in an electrically shielded room, in front of a desk-mounted stereoscope, approximately 45cm from a gamma-corrected CRT monitor refreshing at 109 Hz. Left-eye and right-eye images were displayed side by side, but presented only to their respective eyes via the mirror stereoscope (Stereo Aids, Albany, Australia). Initially, participants were allowed time to adjust the viewer so that they observed a single object in three dimensions. For this calibration, two objects, a ball and a sponge, were presented in alternation. These two objects became targets for a subsequent vigilance task.

There were two stimulus presentation rates. At the 0.5 Hz rate (R1) on each trial, two fixation dots were shown on the screen for 1000ms (to maintain stereo fusion in the interval between pictures) followed by a colour photograph, also for 1000ms (see Figure 1A). At the 1 Hz rate (R2) the fixation dots and colour photograph each appeared for only 500ms. The task was to passively view the pictures through a stereoscopic viewer, except that participants had to report the two target items (ball and sponge) whenever they appeared (with these trials excluded from the subsequent data analysis).

There were object and no-object trials, 180 of each in a block. The object trials were further divided into precision grip (pinch-grip objects) and power grip (grasp objects). Because the number of trials proved to be sufficient to pick out meaningful differences between object categories, we present an analysis based on all three conditions. For the vigilance task, the ball and sponge pictures were included in an additional 16 trials. Trials in each object category and those of the vigilance task were presented in a randomised order.

There were two viewing postures. For the right-hand forward posture (Right), the right hand rested close to the screen with the body rotated approximately 45° away from the screen towards the left. The head was maintained directly facing the screen. For the left-hand forward posture (Left), the left hand rested close to the screen with the body rotated approximately 45° away from the screen towards the right. Again, the head was maintained facing directly towards the screen (see Figure 1B).

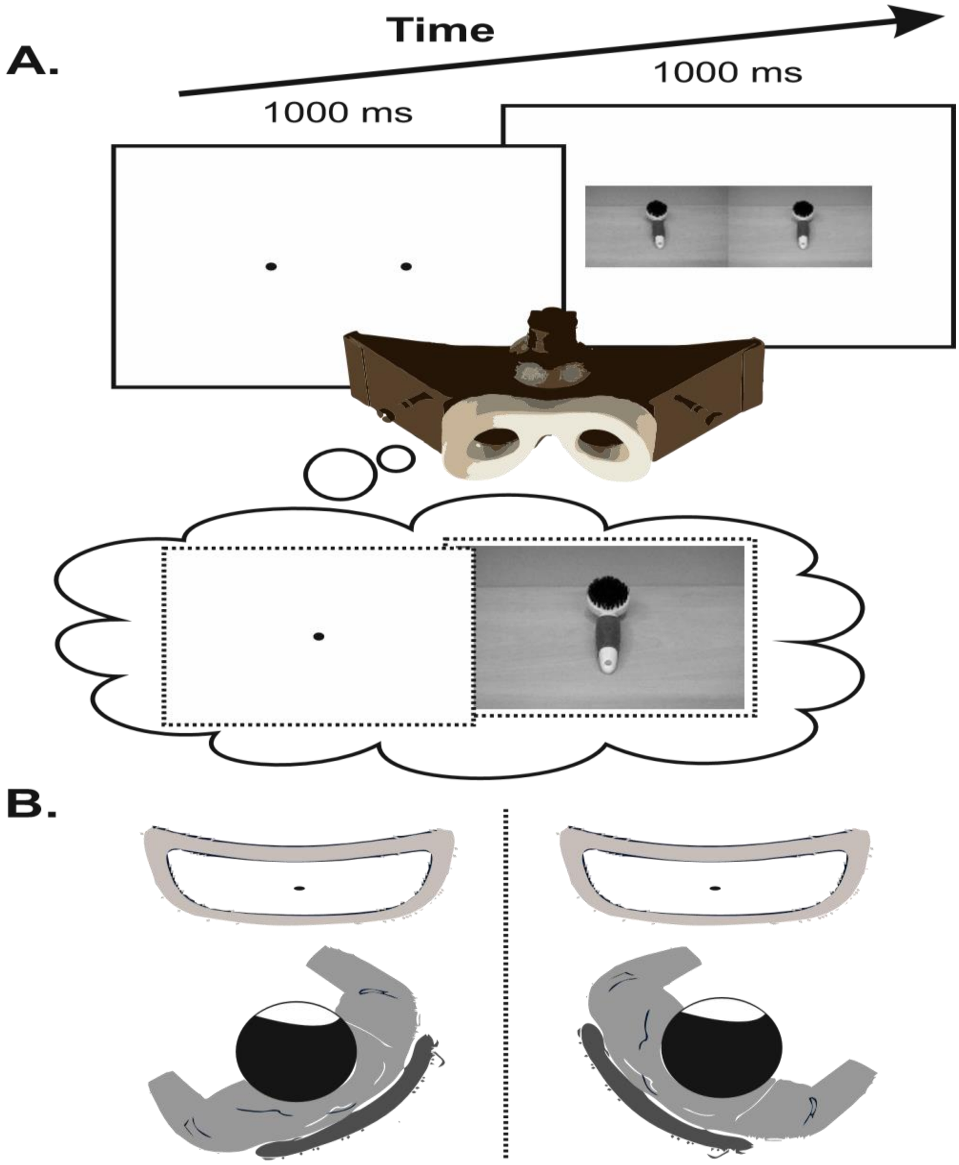

Figure 1. Schematic of Experimental Methods. **A.** Example trial from the EEG paradigm with a 0.5 Hz presentation rate. Here a whole-hand grasp object is displayed (both in stereo, as presented, and as perceived through the stereoscopic viewer, with left and right images fused). **B.** Schematic showing Posture 1 with right (dominant) hand closer to the screen and Posture 2 with left hand closer to the screen; in each case the head is maintained directly facing the screen.

Each participant completed four blocks, with the order of blocks cycled (across participants) through four possible orderings (of posture nested within presentation rate – i.e. R1Right, R1Left, R2Right, R2Left vs. R1Left, R1Right, R2Left, R2Right vs. R2Right, R2Left, R1Right, R1Left vs. R2Left, R2Right, R1Left, R1Right). For the 0.5 Hz rate (R1), in each posture a block lasted approximately 13 minutes, while at 1 Hz (R2), in each posture a block lasted approximately 6½ minutes. In both timings, participants were offered a short break after 126 and 252 trials.

2.4. EEG measurement and analysis

A 64-channel electrode cap was fitted to the participant's head with the ground electrode at position AFZ and the reference electrode at position FCZ. An additional vertical electro-oculogram electrode was placed below the left eye. EEG was recorded at a sampling rate of 1000 Hz. Recording and pre-processing of the EEG data were performed with a BrainAmp DC amplifier and the BrainVision Recorder software (Brain Products, Herrsching, Germany).

For the ERP analysis the data were band-pass filtered offline with high-pass frequency of 0.1Hz and a low-pass frequency of 35Hz and re-referenced to mastoids. Data were segmented into epochs; for R1 the 1100ms from 100ms prior to stimulus onset to 1000ms after stimulus presentation and for R2 the 1000ms from 100ms prior to stimulus onset to 900ms after stimulus presentation. The Gratton and Coles method (Gratton et al. 1983) was used for ocular correction, and baseline correction was applied using a window from 100ms to 0ms before the stimulus. Epochs were also excluded automatically if any values exceeded a threshold of ± 100µV, resulting in a rejection rate of ~10%.

Analyses of ERPs focused on both N1 and N2 components. The prominent N1 negative component was assessed for differences in both anterior and posterior activity. Of greater interest, however, was the anterior N2, previously inferred to reflect the presence or absence of an affordance (Proverbio et al., 2011; Allami et al., 2014; Rowe et al., 2017). All pairwise follow-ups comparing the three object categories were Bonferroni corrected (such that p values reflect a familywise α-level of 0.05 given three possible contrasts).

Based on inspection of averaged data, peak event-related potential (ERP) amplitudes for the anterior N1 component were computed at the F1 and F2 electrodes in the interval 100ms to 180ms after stimulus onset. For the posterior N1 component amplitudes were computed at the PO3 and PO4 electrodes in the interval 100ms to 200ms. This extended time interval for the posterior electrodes is because the time-course of the N1 varies across the scalp from anterior to posterior. Again, based on inspection of averaged data, for peak ERP amplitudes, the anterior N2 component at the F1 and F2 electrodes was calculated as the local peak between 280ms and 370ms after stimulus onset. We had planned to repeat the time windows used in our earlier study, with young adults (Rowe et al., 2017), but on inspection of all individual results, although the range of times for N2 peaks was less, we found that the N2 peaked 10ms to 45ms later in the older adults.

Repeated-measures mixed-design ANOVAs were carried out assessing differences in N1 and N2 amplitudes. The two participant groups (stroke survivors and neurologically healthy age-matched controls) were the between-subjects factor, the within-subject factors being posture (left and right hand forward), presentation rate (R1 and R2), hemisphere (left and right) and the stimulus categories (grasp, pinch-grip and empty desk). We compared manipulable objects that were not necessarily tools (for instance, we included a box and a sweet) to no object (on the same desk backdrop) to discover whether resulting EEG recordings for all manipulable objects showed activity similar to that found more readily in previous studies for tools only (e.g. Proverbio et al. 2011; Righi et al. 2014). Analysis was undertaken to compare any differences between the two categories of objects in relation to the type of grip they might afford (pinch-grip or whole-hand grasp) as well as between each category of object and the empty desk. The Greenhouse-Geisser correction was used to correct for any violations of sphericity.

3. Results

3.1 Anterior electrodes (F1/F2)

3.1.1 The anterior N1 component

We measured the anterior N1 at sites F1 and F2 in order to assess differences in *early motor-system* activity for our various conditions. The ANOVA revealed a main effect of stimulus category, $F(2, 46) = 16.630$; $p < .001$, $\eta p^2 = .420$. Statistically significant differences were shown between the grasp objects and the empty desk, $p = .016$ and between the pinch-grip objects and the empty desk, $p < .001$. There was no significant difference between the two types of objects, $p = .197$.

There was also a significant interaction between presentation rate and stimulus category, $F(2, 46) = 4.020$; $p = .041$, $\eta p^2 = .149$. Follow up one-way ANOVAs across stimulus categories were significant for both presentation rates (see Figure 2a for means, collapsed across participant groups, postures and hemispheres; see also Figure 3 for grand mean ERPs in all conditions separately). For the 0.5Hz presentation rate (R1), follow-up pairwise comparisons showed that there were significant differences between each object category and the no object category; between the grasp object stimuli and no object $p = .010$ and between the pinch-grip object stimuli and the no object stimuli $p < .001$. For the 1Hz presentation rate (R2) there were significant differences between the pinch-grip object and the grasp object stimuli, $p = .028$ and between pinch-grip object and the no object stimuli, $p < .001$.

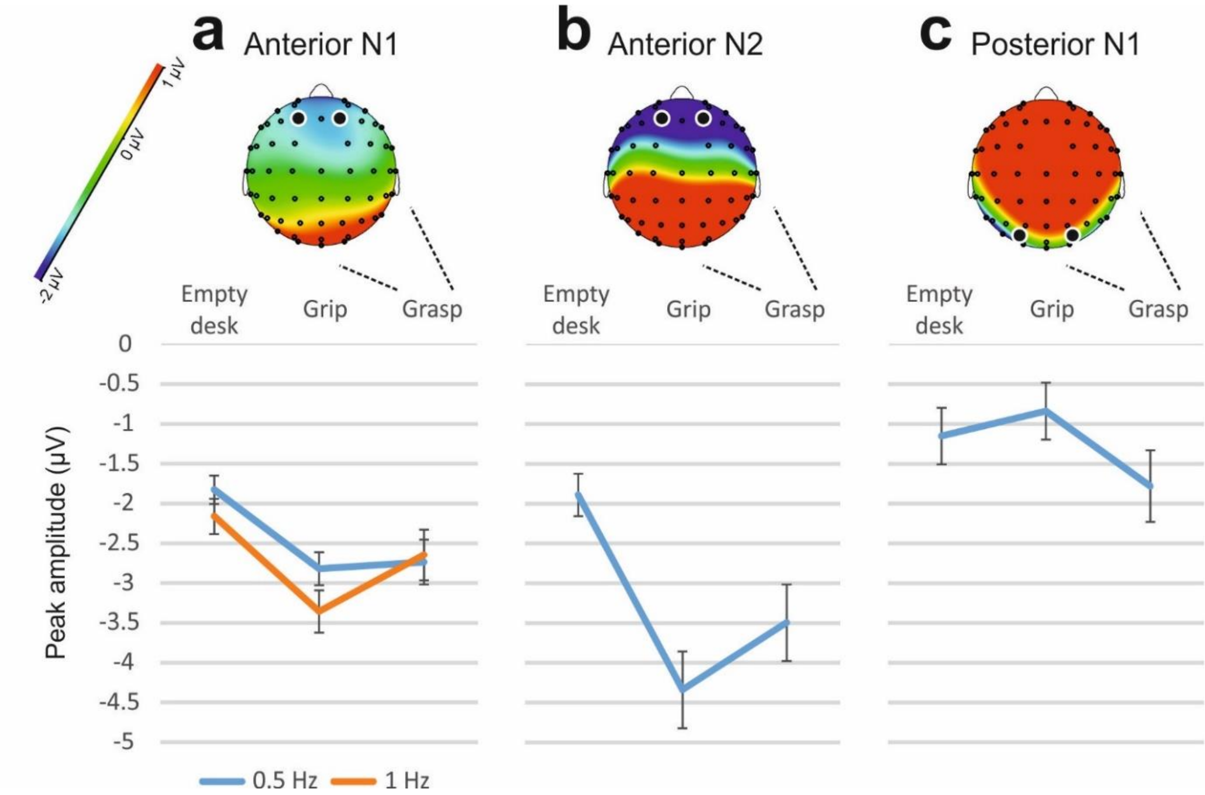

Figure 2. Mean peak ERP amplitudes. Error bars show standard errors. Contributing electrodes are highlighted (larger black circles) in topoplots. **A.** Bottom: Mean anterior N1 for each stimulus category and presentation rate, reflecting the interaction observed via ANOVA for these factors. Top: Topoplot shows grasp stimulus activity in control group at 140-160 ms. **B.** Mean anterior N2 for each stimulus category, reflecting the main effect (and lack of interaction) observed via ANOVA for this factor. Topoplot shows grasp stimulus activity in control group at 303-325 ms. **C.** Mean posterior N1 for each stimulus category, reflecting the main effect (and lack of interaction) observed via ANOVA for this factor. Topoplot shows grasp stimulus activity in control group at 175-200 ms.

3.1.2 The anterior N2 component

We measured the anterior N2 at sites F1 and F2 in order to assess differences in *late motor-system* activity for our various conditions. Figure 2b shows differences in mean ERP amplitude across stimulus categories, and Figure 3 shows the waveforms for each stimulus category in all cells of the design. In all cases, the N2 peak is larger (more negative) for each of the object categories compared to the no-object category.

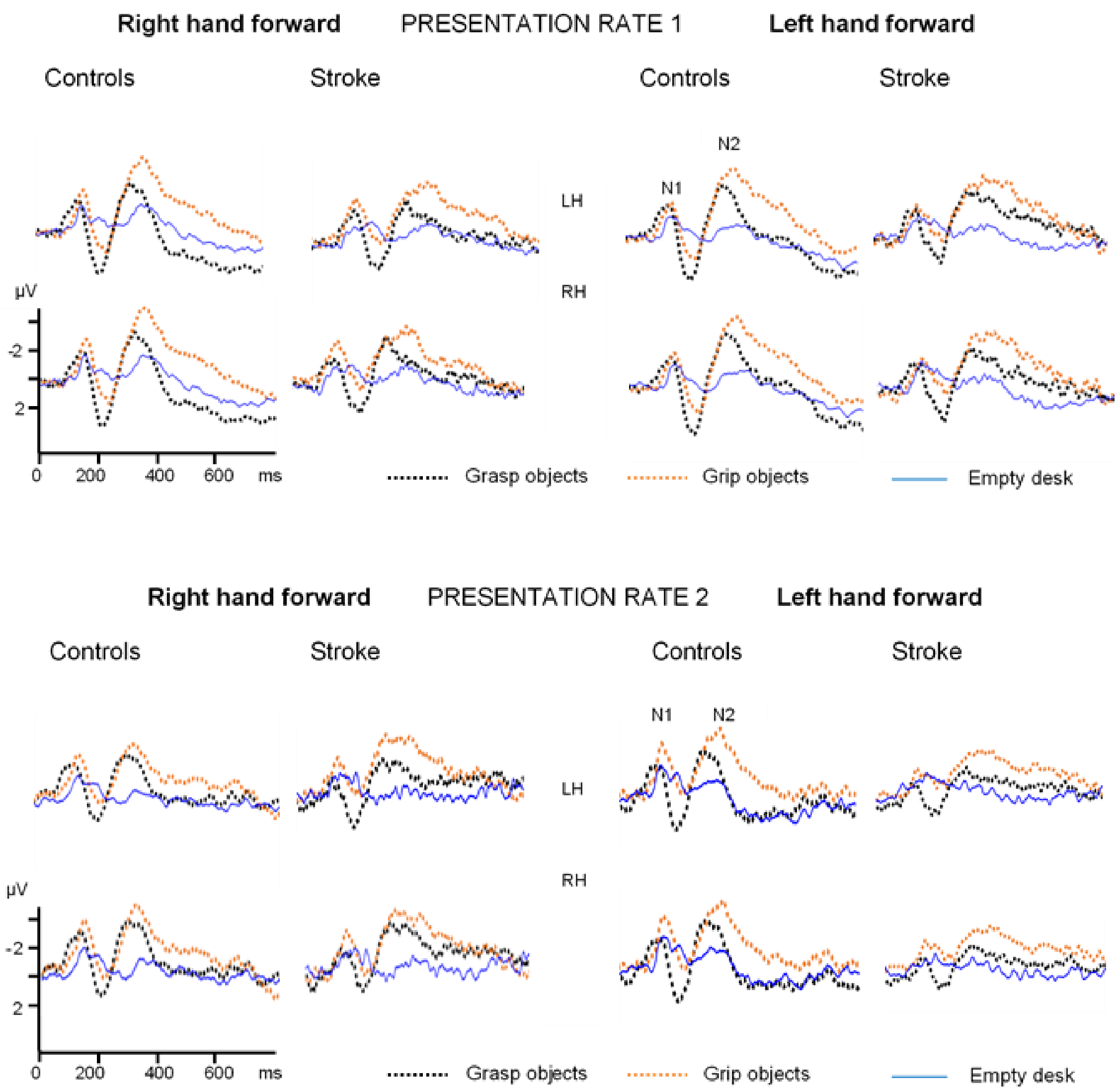

Figure 3. Waveforms (at electrodes F1/F2) from both participant groups for both postures at the 0.5Hz presentation rate (top) and at the 1Hz presentation rate (bottom). The N2 peak is noticeably greater for both object stimulus categories compared to the empty desk (no object category). LH = left hemisphere, RH = right hemisphere.

Differences were again addressed via a 2x2x2x2x3 ANOVA. Most relevant for this investigation was a significant main effect of stimulus category, $F(2, 46) = 33.038$; $p < .001$, $\eta p^2 = .590$. Pairwise follow-ups showed significant differences between grasp object stimuli and pinch-grip object stimuli; $p = .006$, and for both types of object stimuli compared to the no object stimuli; $p < .001$. There were no other main effects.[1]

3.2 Posterior electrodes (PO3/PO4)

3.2.1 The posterior N1 component

We measured the posterior N1 at sites PO3 and PO4 in order to assess differences in *visual-system* processing for our various conditions (Figure 2c). A posture by presentation rate by hemisphere by stimulus category by participant group (2x2x2x3x2) ANOVA revealed only a significant main effect of stimulus category, $F(2, 46) = 4.496$; $p = .016$, $\eta p^2 = .164$. Pairwise follow-ups revealed significant differences just between the grasp object stimuli and pinch-grip object stimuli with $p = .010$. There were no significant interactions involving stimulus category.

4. Discussion

This experiment investigated object-related brain activity in stroke survivors with ongoing upper limb deficits, relative to that of neurologically healthy people of a similar age. We presented participants with three-dimensional photographs of either whole-hand grasp or

[1] The ANOVA showed just one significant interaction, with limited theoretical relevance; that of posture by hemisphere by participant group with $F(1, 23) = 4.681$; $p = .041$, $\eta p^2 = .169$. However, running separate ANOVAs to interpret this interaction produced only non-significant results (considered separately for each participant group, the posture x hemisphere interaction was non-significant; both for the stroke group $p = .092$ and for the control group $p = .729$).

pinch-grip objects on a desk, or just the empty desk, and positioned their bodies to vary whether those objects could be reached easily with the dominant hand (while holding visual stimulation constant). All healthy controls and most stroke survivors had right-hand dominance although some who were right-handed prior to stroke had developed compensatory left-hand dominance. We then recorded brain activity while participants observed stimuli presented at a rate of 0.5Hz and also presented at a rate of 1Hz.

We assessed both early (N1) activity and late (N2) object-evoked motor activity in both the stroke survivors and the healthy controls. The main effect of stimulus category was our key result, with greater activity recorded when viewing the objects compared to viewing the empty desk in both groups. This suggests an affordance effect occurring post stroke. In fact, further affordance specificity was shown from differences in N2 activity for objects requiring differing types of grip; precision (pinch) grip and whole-hand (power) grasp. Again, this result was evident in the post-stroke group as well as the control group. Therefore, as affordance-related motor priming can be generated in those recovering from a stroke, a basic-science justification for investigating optimum presentation rates of objects during rehabilitation can be said to exist.

Affordances are, by definition, a motoric rather than purely visual effect, and our stimuli contained substantial visual differences in addition to their implications for action. Hence a more robust indication of affordance-related motor priming would have come from a significant interaction between posture and stimulus category, especially if found in the dominant left hemisphere, as in our previous experiment (Rowe et al., 2017). However, much younger volunteers were recruited to that study, with a mean age 28 years, whereas in the current study with older participants the mean age across both stroke and healthy control groups was 69 years. As well as the N2 occurring slightly later in the older adults (up to 10ms), perhaps as a result of increased age, we must also consider possible reduction in hemispheric asymmetry due to increasing age (Cabeza, 2002; Ward and

Frackowiak, 2003; Wu and Hallett, 2005; Zimerman et al., 2014; Graziadio et al., 2015). In the control subjects, greater bilateral activity (and the implied greater ambidexterity) could explain why for the N2 there was no significant posture by stimulus category interaction, nor any significant differences between hemispheres. Ward and Frackowiak (2003) performed a comprehensive behavioural and fMRI study, recruiting 26 subjects with ages ranging from 26 to 80. Participants carried out a motor grip task, squeezing two bars together to percentages of their own individual maximal voluntary contraction (MVC). The dominant right hand and non-dominant left hand were tested in separate sessions. fMRI showed age-related differences, some of which identified greater right-hemisphere activity during dominant hand grip for older compared to younger participants. The authors believed this was due to lessened ipsilateral cortical deactivation because of reduced transcollosal inhibition, caused by advancing age. Our results would be in line with this.

Turning to the posterior N1 component, our results showed differences between the two object categories (between pinch-grip and whole hand grasp objects). This was contrary to our earlier study where there were no significant differences between any of the three stimulus categories. Even so, similarly to that study we did not find a difference between pictures of either type of objects compared to the no-object category so it would appear that each type of object was, in fact, visually processed in a broadly similar manner to the empty desk. The different pattern of means observed for the posterior N1 (presumably a sensory component) compared to the two anterior components (which we used to assess the motor system) provides some evidence that our anterior effects should indeed be considered as motoric, because whereas the posterior N1 was, if anything, modulated by visual characteristics (i.e. grasp objects being much larger in general), the anterior components seemed to reflect functional differences (i.e. the presence of a manipulable object).

For the anterior N1 component there were significant differences between the no-object stimulus category and each of the two object categories at the slower, 0.5Hz presentation rate. At the faster, 1Hz presentation rate there were significant differences between the pinch-grip stimuli and the other two categories. In fact, the greatest difference in microvolts for the N1 peak occurred between no object and the small, pinch-grip objects, rather than the larger, whole hand grasp objects, again suggesting that this result was not driven by visual complexity. In our previous study, the only significant difference was between the pinch-grip objects and the no-object category. This new result, particularly at the 0.5Hz rate of stimuli presentation, gives a strong indication that affordance-related motor priming is evident as early as the anterior N1, within 180ms of onset of stimulus.

A recent TMS study (Franca et al. 2012) revealed facilitation in FDI compared to ADM and opponens pollicis (OP) muscles when actual small objects were presented. Previous studies had provided evidence favouring right-hand representation of precision grip over power grasp (Vainio et al., 2006 and 2007) so the authors chose objects that normally evoke a thumb to index finger precision grip. Participants closed their eyes until cued by a sound. Shortly thereafter a box was illuminated for 300ms, showing the presence or absence of an object. A TMS pulse was delivered over left motor cortex at 120ms, 150ms or 180ms after stimulus onset. EMG analysis revealed a significant main effect of ‘object presence’ for the FDI only, and although the timing of delivery of TMS for FDI was not significant per se, further analysis showed a significant difference between object and no object at the 120ms time point but not at the later times. In our current experiment, the N1 amplitude between 100ms and 180ms was correspondingly larger for the object categories compared to the no object category.

While the N2 has already been identified as an indicator of affordance (Proverbio et al, 2011; Allami et al, 2014) our anterior N1 result (comparable to the facilitation found by Franca et. al. 2012) would suggest an earlier affordance onset. Our EEG data and analysis differed from that of their TMS experiment as it was averaged for each hemisphere, over 360 trials for each participant with two different stimulus presentation rates in two postures and across participants. Consequently, identifying a specific time-point of greatest N1 amplitude in our data would not necessarily correspond with the result of Franca et al. where TMS pulses were delivered at three distinct time-points. However, like other TMS studies, e.g., Buccino et al. (2009) and Makris et al. (2011) where facilitation was present at 200ms and 300ms respectively, the N2 we observed between 280ms and 370ms may signify continued motor activation relating to an already primed action affordance.

Presenting stimuli at different rates, 0.5Hz and 1Hz, produced no significant differences in respect of the N2 as for each rate, both types of object stimuli produced significantly larger peak amplitude than the empty desk. Similar significant differences were also observed for the anterior N1 but only at the slower, 0.5Hz presentation rate. The latter result suggests that for any possible benefit of early affordance-related brain activity in stroke rehabilitation interventions, such as virtual reality games, objects should be presented at around 0.5Hz but not as fast as 1Hz.

Like our previous study in young healthy adults, our results again complement and extend those of Proverbio et al. (2011) and Proverbio (2012) who investigated EEG markers for automatic object-action priming. In their work, pictures of objects affording action were contrasted with pictures of objects that did not afford any actions, and effects were found in the N2 (and later), with a swLORETA analysis linking this effect to motor regions of the brain. However, in this study we included the additional element of comparison between healthy older-age adults and neurologically damaged older adults. One limitation of our research was the relatively small size of our sample, which limits power, particularly for the detection of differences between control and stroke survivor groups. It is possible that subtle differences relating to the processing of different object categories would have emerged if a larger sample had been available.

Hand dominance was not fully investigated here but would have been explored further for a larger stroke survivor cohort. Each stroke participant regarded their right hand as their dominant hand prior to stroke. Two participants with left-hemisphere stroke still retained use of their right hand (LI index 43 and 56) and right-hand dominance was preserved for the two participants who had right-hemisphere stroke. Given reduced stamina levels after stroke, and the length of time necessary for the setting up and carrying out the EEG, limited tests were conducted to determine the extent of deficits that might affect upper limb motor output. Any further investigations would require at least an apraxia test such as the Test to Measure Upper Limb Apraxia (TULIA). The Fugl-Meyer assessment was not deemed essential for this specific study because objects were presented as if they would be in reach of the hand closest to the screen. The 9-hole peg test was therefore regarded as the most suitable, but future work conducted in a clinical setting would benefit from a fuller range of assessments, better reflecting clinical norms. Although the heterogeneity of stroke patients used here represents an important limitation for our study, it remains noteworthy that there were no significant hemispheric differences in N1 and N2 waveforms between stroke and control participants. If stroke patients were, for example, now generating affordances only in their intact hemisphere, we would have anticipated some change in waveform topography. In any event, for both participant groups, reduction in hemispheric asymmetry due to increasing age must be considered (Cabeza, 2002; Ward and Frackowiak, 2003; Wu and Hallett, 2005; Zimerman et al., 2014; Graziadio et al., 2015). This may explain why posture did not modulate the affordance effect here, in contrast to our previous work with young adults (Rowe et al. 2017). Perhaps the positioning of the dominant hand relative to an object has less functional relevance in the mature brain.

Conclusion

Even after reduced function of the hand caused by stroke, passively observing manipulable objects results in brain activity consistent with the existence of automatic affordances within the motor system. Here we have shown in stroke survivors and in healthy age-matched controls that between 280ms and 370ms after stimulus onset the evoked anterior ERP N2 component differed between the two categories of manipulable object (whole-hand grasp and pinch-grip) and between an empty desk and the two types of object placed on that desk.

Our examination of the anterior N1 component, between 100ms and 180ms, also resulted overall in significantly larger peak amplitudes for each object category compared to no object. This was also the case specifically at the slower (0.5Hz) presentation rate but not at the faster (1Hz) rate. Taken together, the above time scales for the generation of affordance-related motor priming, between 100ms and 370ms are in agreement with previous studies (Franco et al., 2012; Allami et al. 2014). Knowledge of such onset and offset of affordance activity could be incorporated into interventions to aid improved upper limb rehabilitation outcomes after stroke, particularly for timed re-introduction of objects in virtual reality game interventions. However, each individual in the stroke survivor cohort was at least 2 years post-stroke without a specific diagnosis of apraxia as a reason for their decreased upper limb function. Therefore, we recommend further EEG studies with participants having varying degrees of apraxia to determine the extent of affordance-like activity in this condition.

Conflict of interest statement

None declared.

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

References

Allami, N., Brovelli, A., Hamzaoui , E.M., Regragui , F., Paulignan , Y., Boussaoud, D. 2014. Neurophysiological correlates of visuo-motor learning through mental and physical practice. *Neuropsychologia*, 55(1), pp. 6–14. Available at: http://dx.doi.org/10.1016/j.neuropsychologia.2013.12.017.

Benjamin, E.J., and 45 others on behalf of the American Heart Association Statistics Committee and Stroke Statistics Subcommittee 2017 Heart Disease and Stroke Statistics—2017 Update: A Report From the American Heart Association. *Circulation*, 135, (10), pp e146-e603. https://doi.org/10.1161/CIR.0000000000000485

Buccino, G., Sato, M., Cattaneo, L., Rodà, F and Riggio, L. 2009. Broken affordances, broken objects: A TMS study. *Neuropsychologia*, 47(14), pp. 3074–3078. Available at: http://linkinghub.elsevier.com/retrieve/pii/S0028393209002954.

Cabeza, R. 2002. Hemispheric Asymmetry Reduction in Older Adults: The HAROLD Model*, Psychology and Aging*, 17 (1), pp. 85–100. Available at DOI: 10.1037//0882-7974.17.1.85

Cardellicchio, P., Sinigaglia, C. & Costantini, M., 2011. The space of affordances: a TMS study . *Neuropsychologia* , 49 (1873-3514 (Electronic)), pp. 1369–1372. Available at: http://www.ncbi.nlm.nih.gov/pubmed/21241716.

Carr, J.H. and Shepherd, R.B. 1987. A motor relearning programme for stroke. London: William Heinemann Medical Books.

Dovern A , Fink, G.R. and Weiss, P.H. 2012. Diagnosis and treatment of upper limb apraxia *Journal of Neurology* , 259, pp. 1269–1283

Folstein M.F., Folstein and S.E., McHugh, P.R. 1975. Mini-mental state: A practical method for grading the cognitive state of patients for the clinician. *Journal of Psychiatric Research,* 12(3), pp. 189-198.

Franca, M., Turella, L., Canto, R., Brunelli, N, Allione, L., Andreasi, N.G., Desantis, M., Marzoli, D., Fadiga, L. 2012. Corticospinal facilitation during observation of graspable objects: A transcranial magnetic stimulation study, *PLoS ONE,* 7(11): e49025. doi:10.1371/journal.pone.0049025

Gibson, J.J, 1977. The theory of affordances. In R. Shaw and J Bansford (Eds.), *Perceiving, acting and knowing* (pp. 67-82). Hillsdale, New Jersey: Erlbaum

Gibson, J. J. (1979/1986). *The ecological approach to visual perception*. Boston:Houghton-Mifflin

Gratton, G., Coles, M.G.H. and Donchina, E., 1983. A new method for offline removal of ocular artefact. *Electroencephalography and clinical Neurophysiology*, 55, pp.464-484

Graziadio, S., Nazarpour, K., Gretenkord, S., Jackson, A and Eyre, J.A. 2015. Greater intermanual transfer in the elderly suggests age-related bilateral motor cortex activation is compensatory. *Journal of Motor Behavior*, 47 (1), pp. 47-55

Grèzes, J., Tucker, M., Armony, J., Ellis, R. and Passingham, R.E. 2003. Objects automatically potentiate action: an fMRI study of implicit processing. *European*

Journal of Neuroscience, 17(12), pp. 2735–2740. Available at: http://doi.wiley.com/10.1046/j.1460-9568.2003.02695.x.

Hopf, J-M., Vogel, E., Woodman, G. Heinze, H-J. and Luck, S.J. 2002. Localizing visual discrimination processes in time and space. *Journal of Neurophysiology*, 88, pp. 2088-2095.

Kühn, S., Werner, A., Lindenberger, U., and Verrel, J. 2014. Acute immobilisation facilitates premotor preparatory activity for the non-restrained hand when facing grasp affordances. *NeuroImage*, 92, pp. 69–73

Makris, S., Hadar, A. A. & Yarrow, K., 2011. Viewing objects and planning actions: On the potentiation of grasping behaviours by visual objects. *Brain and Cognition*, 77(2), pp. 257–264. Available at: http://dx.doi.org/10.1016/j.bandc.2011.08.002.

Makris, S., Hadar, A.A. & Yarrow, K., 2013. Are object affordances fully automatic? A case of covert attention. *Behavioral Neuroscience*, 127(5), pp. 797–802. Available at: http://doi.apa.org/getdoi.cfm?doi=10.1037/a0033946.

Mangun, G.R., and Hillyard, S.A. 1991. Modulations of sensory-svoked brain potentials indicate changes in perceptual processing during visual-spatial priming. J*ournal of Experimental Psychology: Human Perception and Performance*,17(4) pp. 1057-1074

Melmoth, D.R., Storoni, M., Todd, G., Finlay, A.L. and Grant, S. 2007. Dissociation between vergence and binocular disparity cues in the control of prehension. *Experimental brain research*, 183(3), pp. 283–98. Available at: http://www.ncbi.nlm.nih.gov/pubmed/17665181.

Melmoth, D.R., Finlay, AJ., Morgan, M.J. and Grant, S. 2009. Grasping Deficits and Adaptations in Adults with Stereo Vision Losses. *Investigative Opthalmology & Visual Science*, 50(8), p. 3711. Available at: http://iovs.arvojournals.org/article.aspx?doi=10.1167/iovs.08-3229.

Melmoth, D.R. & Grant, S. 2006. Advantages of binocular vision for the control of reaching and grasping. *Experimental Brain Research*, 171(3), pp. 371–388.

Murata, A., Fadiga, L., Fogassi, L., Gallese, V., Raos, V. and Rizzolatti, G. 1997. Object representation in the ventral premotor cortex (area F5) of the monkey. *Journal of neurophysiology*, 78(4), pp. 2226–2230.

Oldfield, R.C. 1971. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia*, 9(1), pp. 97–113. Available at: http://linkinghub.elsevier.com/retrieve/pii/0028393271900674\npapers3://publication/doi/10.1016/0028-3932(71)90067-4.

Pazzaglia, M., Smania, N., Corato, E.,and Aglioti, S.M. 2008 Neural underpinnings of gesture discrimination in patients with limb apraxia *The Journal of Neuroscience*, 28(12), pp. 3030 –3041

Pekna, M., Pekny, M., Nilsson, M. 2012. Modulation of neural plasticity as a basis for stroke rehabilitation. *Stroke*, 43, pp. 2819-2828 Availabe at DOI: 10.1161/STROKEAHA.112.654228

Proverbio, A.M. 2012. Tool perception suppresses 10-12Hz µ rhythm of EEG over the somatosensory area. *Biological Psychology*, 91(1), pp. 1–7. Available at: http://dx.doi.org/10.1016/j.biopsycho.2012.04.003.

Proverbio, A.M., Adorni, R. & D'Aniello, G.E. 2011. 250 Ms To Code for Action Affordance During Observation of Manipulable Objects. *Neuropsychologia*, 49(9), pp. 2711–2717. Available at: http://dx.doi.org/10.1016/j.neuropsychologia.2011.05.019.

Randerath, J., Goldenberg, G., Spijkers, W., Li, Y & Hermsdörfer, J. 2011. From pantomime to actual use: How affordances can facilitate actual tool-use. *Neuropsychologia,* 49, pp. 2410– 2416

Rice, N.J., Valyear, K.F., Goodale, M.A., Milner, A.D. and Culham, J.C. 2007. Orientation sensitivity to graspable objects: an fMRI adaptation study. NeuroImage, 36 Suppl 2(3), pp. T87-93. Available at: http://www.ncbi.nlm.nih.gov/pubmid/17499174.

Righi, S., Orlando, V. & Marzi, T. 2014. Attractiveness and affordance shape tools neural coding: Insight from ERPs. *International Journal of Psychophysiology*, 91(3), pp. 240–253. Available at: http://dx.doi.org/10.1016/j.ijpsycho.2014.01.003.

Rowe, P.J., Haenschel, C., Kosilo, M., Yarrow, K. 2017. Objects rapidly prime the motor system when located near the dominant hand. *Brain and Cognition*, 113, pp. 201-108

The Stroke Association 2018. *State of the Nation Stroke statistics - February 2018* https://www.stroke.org.uk/sites/default/files/state_of_the_nation_2018.pdf

Thorpe, S. J., Fize, De., & Marlot, C. (1996). Speed of processing in the human visual system. *Letters to Nature*, *381*, 520‐522.

Tucker, M. & Ellis, R. 1998. On the relations between seen objects and components of potential actions. *Journal of experimental psychology. Human perception and performance*, 24(3), pp. 830–846.

Tucker, M. & Ellis, R. 2001. The potentiation of grasp types during visual object categorization. *Visual Cognition*, 8(6), pp. 769–800. Available at: WOS:000172392900004.

Vainio, L., Ellis, R., Tucker, M. and Symes, E. 2006. Manual asymmetries in visually primed grasping. *Experimental Brain Research*, 173, pp. 395–406 Available at DOI 10.1007/s00221-006-0378-x

Vainio, L., Ellis, R., Tucker, M. and Symes, E. 2007. Local and global affordances and manual planning. *Experimental Brain Research*, 179(4), pp. 583-594

Valyear, K.F. Cavina-Pratesi, C., Stiglick, A.J. & Culham, J.C. 2007. Does tool-related fMRI activity within the intraparietal sulcus reflect the plan to grasp? *NeuroImage*, 36, pp. 94–108.

Vogel, E. K., & Luck, S. J. (2000). The visual N1 component as an index of a discrimination process. *Psychophysiology*, *37*, 190‐203. Available at https://doi.org/10.1111/1469-8986.3720190

Wade, E., Chen, C. and Winstein, C.J. 2014. Spectral analyses of wrist motion in indificuals poststroke: The development of a performance measure with promise for unserpervised settings. *Neurorehabilitation and Neural Repair*, 28(2), pp. 169-178

Ward, N.S. and Frackowiak, R.S.J. 2003. Age-related changes in the neural correlates of motor performance. *Brain*, 126, pp. 873-888

Wheaton, L,A., Bohlhalter, S., Nolte, G., Shibasaki, H.,Hattori, N.,Fridman, E., Vorbach, S, Grafman, J. and Hallett, M. 2008. Cortico-cortical networks in patients with ideomotor apraxia as revealed by EEG coherence analysis. *Neuroscience Letters*, 433, pp.87-92

Wu, T and Hallett, M. 2005. The influence of normal human ageing on automaticMovements. *Journal of Physiology* 562 (2), pp. 605–615

Zimerman, M., Heise, K-F., Gerloff, C., Cohen, L.G., and Hummel, F.C. 2014. Disrupting the ipsilateral motor cortex interferes with training of a complex motor task in older adults. *Cerebral Cortex*, 24, pp. 1030-1036 Available at DOI:10.1093/cercor/bhs385