

# Intact Motor Imagery in Chronic Upper Limb Hemiplegics: Evidence for Activity-Independent Action Representations

Scott H. Johnson<sup>1,2</sup>, Gwen Sprehn<sup>2</sup>, and Andrew J. Saykin<sup>2</sup>

## Abstract

■ Four experiments were undertaken to examine the effects of chronic hemiplegia on the ability to internally represent actions involving either the paralyzed (contralesional) or relatively unaffected (ipsilesional) limb. An experimental group of chronic, densely hemiplegic patients was compared with controls who experienced nearly full recovery from an initially dense hemiparesis. All participants suffered cerebral vascular accidents that spared sites in premotor and parietal areas directly involved in representing upper limb actions. Despite chronic limb immobility, hemiplegic patients performed all four tasks at a high level of accuracy and showed no differences in their ability to represent actions of the contralesional versus ipsilesional limbs. On tasks that

involved representing actions of the hands and lower arms, hemiplegic patients were as accurate as recovered controls. Hemiplegic patients were, however, less accurate than controls on a task that involved representing actions of either upper arm. Overall, chronic hemiplegics performed more accurately for decisions based on their contralesional limbs: a “hemiplegic advantage” that may be related to an ongoing focus on planning and/or imagining currently impossible movements. These findings reveal a dissociation between the ability to internally “represent” versus “produce” manual actions. Further, they demonstrate that internal action representations can be robust to even years of limb disuse. ■

## INTRODUCTION

There is considerable evidence that the integrity of representations in primary sensory–motor areas of the mature brain is “activity-dependent” (Kaas, 1991). Decreased use resulting from central (Nudo & Milliken, 1996; Nudo, Milliken, Jenkins, & Merzenich, 1996) or peripheral (Donoghue, Suner, & Sanes, 1990; Sanes, Suner, & Donoghue, 1990) injuries may cause a decrease in the area of cortex devoted to representing the affected body part. Likewise, increased use of a body region may result in larger cortical representations (Nudo, Wise, SiFuentes, & Milliken, 1996; Karni et al., 1995). The activity-dependent nature of cortical representations is of considerable importance for understanding recovery of motor functions following cerebral vascular accidents (CVAs) (Nudo, 1997).

Hemiplegia of the upper limb is one of the most common and devastating effects of CVAs and can result from damage to a wide variety of structures including: primary sensorimotor areas, supplementary motor, premotor, and parietal cortices, basal ganglia, and/or thalamus (Pantano et al., 1996). Severity can range from complete flaccidity to difficulty controlling independent

finger movements (Brunnstrom, 1966). While it is typical for patients to regain some degree of limb function, a minority will achieve full recovery. Conversely, a small percentage of patients will be left with chronic, dense hemiparesis. The consequences of such long-term hemiparesis on the ability to represent actions involving the affected limb are presently unknown. An interesting question concerns whether—like representations in primary sensorimotor cortex—these distributed action representations are activity dependent. Although limited, existing evidence suggests that the ability to execute movements may not be a necessary condition for internally representing actions.

## Effects of Limb Immobility on Internal Action Representations

Research from both monkeys (Johnson, Ferraina, Bianchi, & Caminiti, 1996; Boussaoud, di Pellegrino, & Wise, 1995) and humans (Binkofski et al., 1999; Grafton, Fagg, Woods, & Arbib, 1996) suggests that acts of reaching and grasping are represented in circuits connecting distinct regions of parietal and premotor cortex (reviewed in Jeannerod, Arbib, Rizzolatti, & Sakata, 1995). Indeed, damage to these regions can disrupt the ability to perform or imagine manual actions (Johnson, 2000a; Sirigu et al., 1995, 1996). However,

<sup>1</sup>Dartmouth College, <sup>2</sup>Dartmouth Medical School

there is evidence that patients with paralyzes resulting from lesions to other brain areas may retain the ability to accurately represent actions they can no longer perform (Johnson, 2000a; Hildebrandt & Zieger, 1995; Weiss, Hansen, Beyer, et al., 1994; Weiss, Hansen, Rost, et al., 1994; Decety & Boisson, 1990; Gandevia, 1982).

Recently, Johnson (2000a) showed that hemiplegics, without premotor or parietal damage, can accurately represent prehensile actions involving their paralyzed limbs. On a task that required deciding whether an overhand or underhand grip would be most natural for grasping a handle presented in different orientations, judgments based on the contralesional limb were as accurate as those involving the relatively unaffected, ipsilesional side. Earlier behavioral work demonstrated that healthy subjects engage in “implicit” movement simulations when solving such tasks (Johnson, 2000b). That is, although subjects do not report engaging in mental imagery, the amount of time required to select an overhand or underhand grip is a linear function of the shortest “biomechanically plausible” trajectory from the physical position of the subject’s own hand into the selected posture. Further, for those stimulus orientations that would involve adopting more awkward postures to grasp, decisions were both less accurate—as compared with grip preferences exhibited during actual prehension—and slower. These latter findings concur with a number of previous reports showing that challenging actions are more difficult to imagine (Decety & Michel, 1989; Decety & Jeannerod, 1995; Decety, Jeannerod, & Prablanc, 1989; Parsons, 1987, 1994) or plan (Georgopoulos & Massey, 1987). The fact that some hemiplegic patients retain the ability to accurately represent actions involving their paralyzed limbs shortly after their CVAs (Johnson, 2000a) is an interesting deviation from this pattern. It suggests that internal limb representations have not been recalibrated to reflect the relatively recent loss of function. This observation raises a number of important questions concerning the nature of internal action representations.

Of primary interest in the present study is whether the ability to represent actions is affected by “chronic” limb immobility. If action representations are activity dependent, performances on tasks that involve representing actions based on a chronically paralyzed, contralesional limb should be considerably less accurate than those based on a relatively unimpaired, ipsilesional limb. Alternatively, if action representations are activity independent, then judgments involving both limbs should be comparable in accuracy. If chronic hemiplegics do have difficulty internally representing manual actions, then several additional questions can be entertained: Are effects of disuse specific to the paralyzed limb, or do they affect the ability to represent actions of both limbs? If effects of disuse are limb

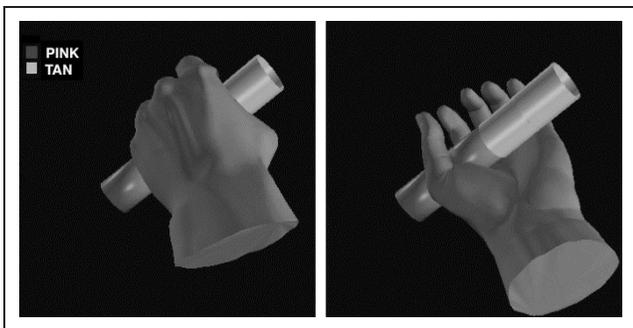
specific, then hemiplegics should perform as well as nonhemiplegic control subjects when representing movements of the ipsilesional limb. However, if limb disuse adversely affects the ability to represent actions involving either limb, then hemiplegics should perform less accurately than controls regardless of the side involved. Does chronic limb disuse differentially affect the ability to represent certain manual actions (e.g., object prehension) while sparing others (e.g., nonprehensile arm movements)? If internal action representations are globally compromised by chronic limb disuse, then hemiplegics should have difficulty performing a variety of different tasks that involve representing actions of the contralesional and/or ipsilesional limb(s). Conversely, to the extent that chronic disuse selectively affects the ability to represent specific actions, hemiplegics might only experience difficulties on certain tasks. Finally, does “transient” loss of limb mobility have any lasting consequences for the ability to internally represent actions? If so, then there are two possibilities. On the one hand, patients who have gradually recovered from an initially dense hemiparesis might have difficulties representing actions involving the formerly paralyzed limb. This would imply that any changes in performances of chronic hemiplegics might not be attributable to continued disuse per se, but rather to having experienced hemiparesis during some critical period after their injuries. On the other hand, it is also possible that patients who have recovered from an initially dense hemiparesis, might actually be “more” accurate at representing actions involving their formerly paralyzed versus ipsilesional limbs. All of these patients underwent intensive inpatient and outpatient rehabilitation that entailed extensive practice planning and controlling manual actions involving the contralesional limb. The increased focus on contralesional limbs during recovery may have resulted in an enhanced ability to internally represent actions in which these effectors are involved.

These questions were addressed by examining performances of patients falling at two extremes of the recovery of function distribution. Members of the experimental, hemiplegic group had experienced complete, or nearly complete, loss of limb mobility for at least 1 year following a CVA. Those in the recovered group had regained nearly all limb functions following an initially dense hemiparesis. Members of both groups had relatively normal use of the ipsilesional limb. In order to avoid confounding hand dominance with the ability to represent actions of the contralesional limb, all patients had lesions in the non-motor-dominant hemisphere. Finally, because the intent was to explore effects of chronic limb disuse on the ability to internally represent actions, none of the patients in either group had lesions affecting areas of premotor or parietal cortex directly associated with these processes.

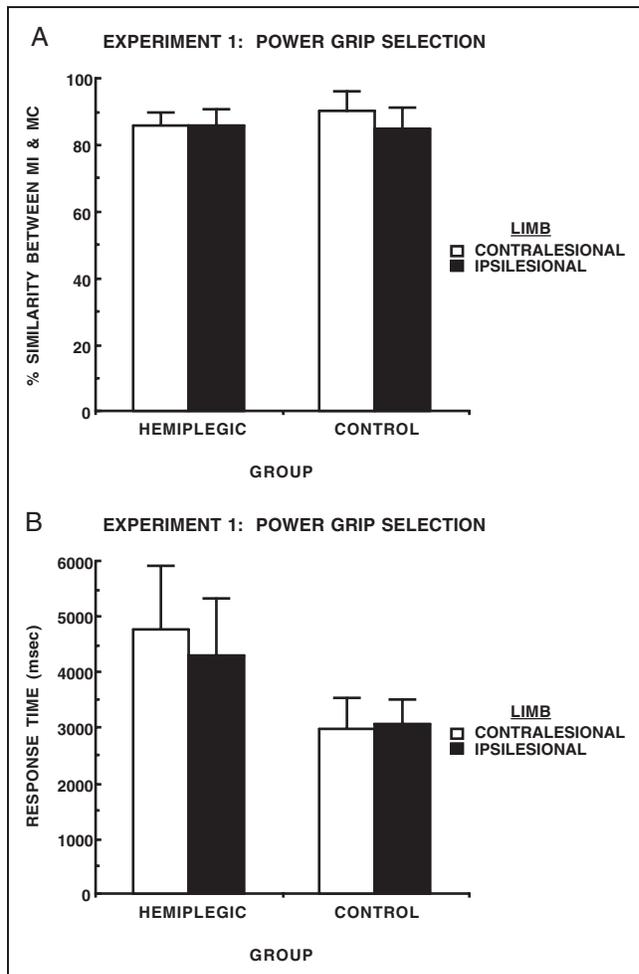
## EXPERIMENT 1: POWER GRIP SELECTION

As discussed above, previous work indicates that when tested soon after the onset of paralysis, hemiplegic patients may retain the ability to accurately represent actions that they can no longer undertake (Johnson, 2000a). The present experiment attempted to replicate this finding in chronically hemiplegic patients using the same power grip selection task.

The accuracy of motor imagery (MI) judgments in this study, and Experiments 3 and 4, was evaluated by direct comparison with results from a nearly identical motor control (MC) condition in which subjects in both groups actually performed the required actions using their ipsilesional limbs (see General Method). As shown in Figure 1, in both the MI and MC conditions, subjects were presented with handles appearing randomly in one of eight different orientations in the picture plane ( $45^\circ$  steps around a full circle). Subjects first performed the MI condition, where the task was to decide whether their thumb would be located on the pink or tan end of the stimulus if they were to grasp it using the most natural power grip. In other words, given the stimulus' orientation, and knowledge of the biomechanical properties of the limb on which their judgments were to be based, would they prefer an overhand or underhand grasp? Patients responded by making a two-choice button press using the uninvolved hand. In the MC condition, they simply reached for the object and grasped it in the preferred manner using the ipsilesional hand. In healthy adults, grip preferences in these MI and MC conditions are highly correlated for both left and right hands ( $R = .94$ ; Johnson, 2000b; Experiment 3). Therefore, if internal action representations supporting these judgments are activity independent, then the same should be true for chronically hemiplegic patients' MI decisions. Conversely, if



**Figure 1.** The power grip selection task. Patients were required to decide whether it would be more natural to grasp a handle using an overhand or underhand grip. Handles appeared randomly in eight different orientations ( $45^\circ$  steps). In the MI task, patients reported whether the preferred grip would involve placing the thumb on the pink or tan end of the handle. Decisions were made based on both the contralesional and ipsilesional limbs in separate blocks. In the MC task, they actually grasped handles using their ipsilesional hand.



**Figure 2.** Accuracy and speed of power grip selection. Panel A shows that groups did not differ significantly on accuracy of MI decisions. Likewise, accuracy was comparable for contralesional and ipsilesional limbs. Panel B indicates that neither group nor limb had a significant effect on RT.

these representations are activity dependent, then judgments should be less accurate—that is, more dissimilar to grip preferences exhibited in the MC condition—when based on their contralesional versus ipsilesional limbs.

## Results and Discussion

Figure 2A shows that both groups performed at an equivalent, high level of accuracy,  $F < 1.0$ . Scores for individual patients can be found in Table 1. Consistent with patients tested during the acute phase of recovery (Johnson, 2000a), the accuracy of MI judgments did not differ significantly between contralesional versus ipsilesional limbs for either group [ $F(1,6) = 3.4, p = .11$ ]. Likewise, the two-way interaction between group and limb was not significant [ $F(1,6) = 3.2, p = .12$ ].

The high degree of accuracy exhibited by our patients when representing actions involving the contralesional

**Table 1.** Percent Accuracy Scores for Judgments based on the Contralesional (CONT) versus Ipsilesional (IPSI) Hands of Subjects in the Experimental (ID Nos. 1–4) and Control (ID Nos. 5–8) Groups

ID	Experiment 1		Experiment 2		Experiment 3		Experiment 4	
	CONT	IPSI	CONT	IPSI	CONT	IPSI	CONT	IPSI
1	84.2	84.2	87.5	85.4	89.1	82.8	89.0	85.9
2	87.5	90.6	97.9	87.5	87.5	37.5	90.6	93.8
3	95.9	96.5	81.3	88.4	59.4	18.8	93.8	90.6
4	76.3	72.2	77.0	58.3	87.5	82.5	84.4	68.8
5	93.8	90.6	95.8	85.4	82.8	82.8	98.4	98.4
6	73.4	67.2	83.3	77.1	65.9	65.3	100	100
7	100	88.75	89.6	85.4	76.7	92.4	100	96.8
8	93.75	93.75	93.8	87.5	71.9	81.3	90.6	100

limb does not appear to come at the cost of reduced speed. As shown in Figure 2B, speed of decisions based on the contralesional limb did not differ from those involving the ipsilesional side ( $F < 1.0$ ). Likewise, there was no significant difference between groups [ $F(1,6) = 1.5, p = .26$ ], nor was there an interaction between limb and group [ $F(1,6) = 2.0, p = .20$ ].

In short, there was no evidence that chronic hemiplegia compromises the ability to internally represent power gripping actions based either on the contralesional or ipsilesional limbs. These findings extend Johnson's (2000a) earlier observations in acute hemiplegics and are consistent with the hypothesis that distributed action representations are robust to effects of limb disuse, that is, they appear to be activity independent.

The next experiment attempts to disconfirm this hypothesis through use of a hand identification task that has been shown to involve internally representing movements of the upper limbs.

## EXPERIMENT 2: IDENTIFICATION OF ROTATED HANDS

Previous work indicates that determining whether pictures depict left or right hands appearing in various orientations involves internally representing movements of one's own limbs (Parsons, 1987, 1994; Cooper & Shepard, 1975). This hypothesis is supported by several lines of work. Evidence from positron emission tomography (PET) indicates that, in addition to other structures, solving this task activates regions of parietal and premotor cortex (Parsons et al., 1995) that are involved in representing manual actions. Indeed, patients with neglect due to right parietal lesions have particular difficulty identifying pictures of contralesional left hands (Coslett, 1998). Finally, a recent transcranial magnetic

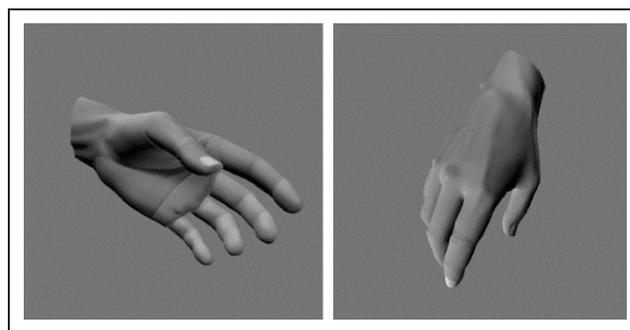
stimulation (TMS) experiment demonstrated that stimulation of primary motor cortex increases the time required to perform these decisions (Ganis, Keenan, Kosslyn, & Pascual-Leone, 2000).

Demands of hand identification differ considerably from those of the power grip selection task used in Experiment 1. First, this task is nonprehensile. Instead of representing how to interact with an object, hand identification requires comparing representations of one's own hands with pictures of someone else's hands. Second, in the hand identification task, there is one, and only one, correct answer, left or right. By contrast, for any given handle orientation, subjects in the grip selection task could choose either an overhand or underhand grip (Figure 1). The decision between these two options cannot be resolved based entirely on information occurring in the visual stimulus, but instead, it must involve accessing an accurate representation of the biomechanical constraints of the involved limb if preferences are to match those displayed in MC.

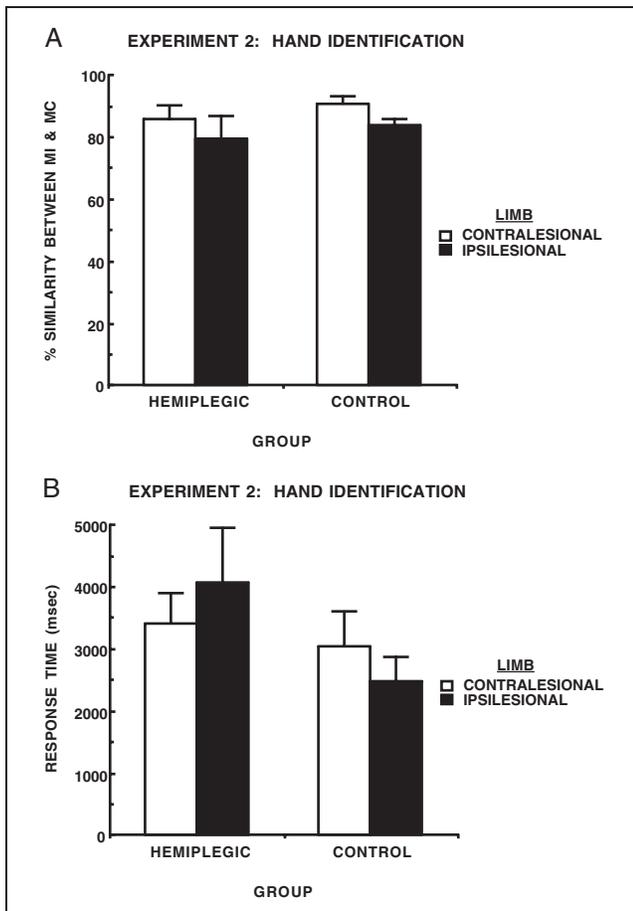
Because hand identification has been widely used to investigate implicit MI, it was of interest to evaluate hemiplegic patients on this task. As shown in Figure 3, this was accomplished with a set of photorealistic depictions of variously oriented left and right hands presented in randomized order. If representations of limb movement involved in solving this task are activity independent, then chronic hemiplegics should again perform equally well when identifying pictures of their contralesional versus ipsilesional hands. Likewise, based on results of Experiment 1, no differences in accuracy are expected between hemiplegic and recovered groups.

## Results and Discussion

As depicted in Figure 4A, there was again no evidence that chronic limb immobility compromises the ability to internally represent movements. Both groups again performed at a comparable, high level of accuracy



**Figure 3.** The hand identification task. Patients were required to decide whether the picture illustrated a left or right hand. As described in the General Method, hands appeared randomly in 60 different three-dimensional orientations.



**Figure 4.** Accuracy and speed of hand identification. Panel A illustrates that performance accuracy did not differ as a function of group or limb. However, there was a nonsignificant trend for patients in both groups to perform more accurately when judgments involved the contralateral limb. Panel B shows that there was a nonsignificant trend for hemiplegic patients to be faster when identifying pictures of their ipsilateral hands. Recovered patients showed an opposite tendency.

( $F < 1.0$ ) (Table 1). In contrast to Experiment 1, the main effect of limb did approach significance [ $F(1,6) = 5.0, p = .07$ ]. However, this reflects a nonsignificant tendency for both groups to perform “more accurately” when judgments involved identifying pictures of the contralateral ( $M = 88.3, SD = 7.4$ ) versus ipsilateral ( $M = 81.9, SD = 10.2$ ) hand. The trend to perform more accurately when identifying pictures of the current, or formerly paralyzed hand, is consistent with the hypothesis that patients may actually have improved their ability to represent actions of the affected limb as a result of extensive rehabilitation focused on the contralateral side. Unexpectedly, this trend was also evident in patients for whom no recovery of function actually took place. If this interpretation is correct, then this experience-dependent effect would be attributable to cognitive rather than movement-related practice. The interaction between limb and group was not significant ( $F < 1.0$ ).

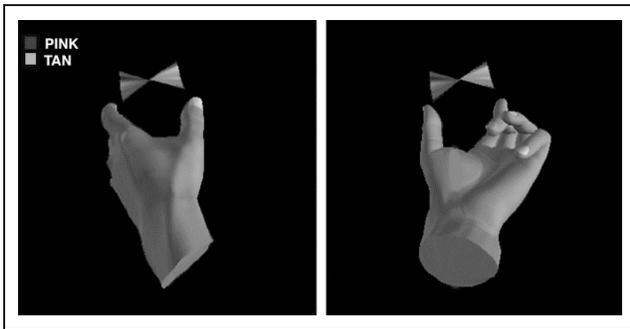
Figure 4B shows that RTs also did not differ between contralateral and ipsilateral limbs ( $F < 1.0$ ). Likewise, there was no significant difference in RT between groups [ $F(1,6) = 1.4, p = .27$ ]. However, the interaction between limb and group did approach significance [ $F(1,6) = 5.2, p = .06$ ]. This is attributable to the fact that currently hemiplegic patients tended to perform faster when decisions involved identifying pictures of their paralyzed ( $M = 3416, SD = 1000$ ) versus ipsilateral hands ( $M = 4083, SD = 1731$ ), while recovered patients performed faster when pictures represented their ipsilateral ( $M = 2498, SD = 732$ ) versus contralateral ( $M = 3034, SD = 1151$ ) hands.

Overall, these results are consistent with those of the previous experiment in suggesting that internal action representations are not adversely affected by extended periods of limb disuse. Chronic and recovered hemiplegic patients perform at least as accurately when making MI judgments based on their contralateral versus ipsilateral limbs.

Thus far, lack of an effect of chronic paralysis on MI judgments in Experiments 1 and 2 has been interpreted as support for the hypothesis that action representations are “activity independent.” However, it can also be argued that the null findings of Experiments 1 and 2 reflect the fact that these tasks were simply not demanding enough to elicit differences between limbs. This seems highly unlikely for two reasons. First, neither experiment’s results suggests the existence of a ceiling effect. Second, the fact that both groups tended to be more accurate in Experiment 2 when judgments involved the contralateral hand runs counter to this suggestion. Nevertheless, the following experiment attempts to rule out this alternative through the use of a task that demands representing more precise manual actions.

### EXPERIMENT 3: PRECISION GRIP SELECTION TASK

Prehensile hand configurations can be divided into two categories: power grips in which the entire hand is used to engage an object, and precision grips in which objects are grasped between the pads of the thumb, forefinger, and/or middle finger (Klatzky, Pellegrino, McCloskey, & Lederman, 1993). There are several reasons why using a precision grip can be considered more demanding than a power grip. Precision grips appear later in development (Forssberg, Eliasson, Kinoshita, Johansson, & Westling, 1991) and are unique to human beings (Marzke, 1997). Likewise, the independent finger control required to form precision grips tends to recover later in hemiplegic patients (Brunnstrom, 1966). Tasks that require precision gripping actions therefore present an ideal opportunity to further scrutinize the hypothesis that hemiplegics can accurately represent actions involving their paralyzed limbs.



**Figure 5.** The precision grip selection task. This task was similar to power grip selection with one important exception: Subjects were required to decide which end of the stimuli their thumbs would be on if they grasped them in the most natural precision grip. Stimuli appeared randomly in eight different picture plane orientations ( $45^\circ$  steps). In the MI condition, they reported the color on which they would place their thumb. Judgments based on contralesional and ipsilesional limbs were run in separate blocks. In the MC condition, they actually grasped widgets using the ipsilesional hand.

As illustrated in Figure 5, subjects were required to determine which end of a widget (pink or tan) their thumb would be on if they grasped it in the most natural manner between the pads of the thumb and forefinger. As in Experiment 1, widgets were presented randomly in eight different orientations in both MI and MC conditions. Importantly, pilot testing with healthy subjects revealed that the end on which the thumb was placed during MC differed substantially from the results obtained in the MC power gripping task (Experiment 1). Consequently, accurate MI responses could only be achieved in the present task if subjects were complying with the instruction to “determine how they would grasp the widgets using a precision grip.”

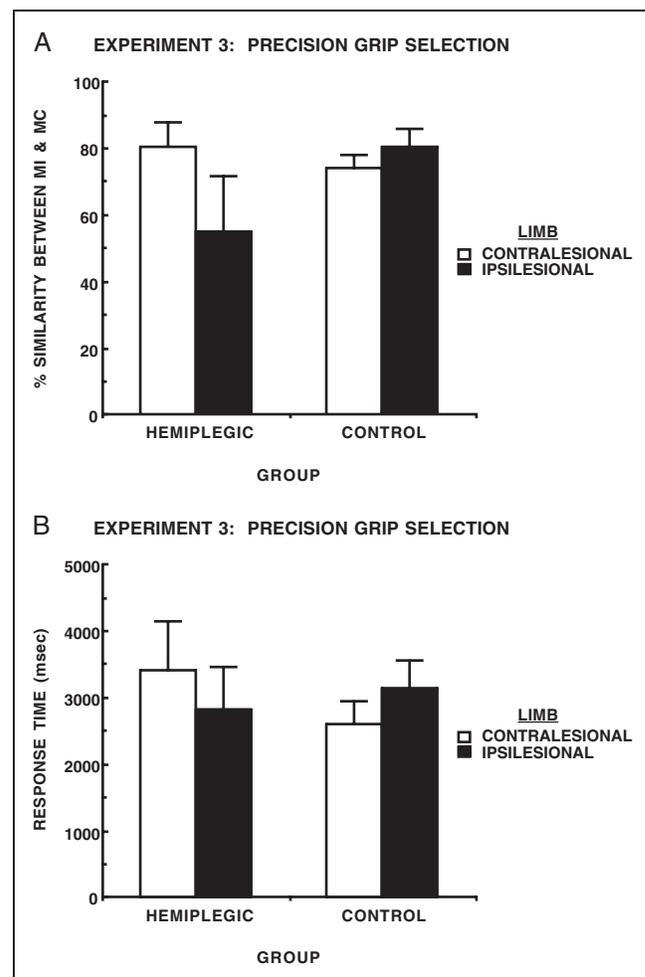
If the ability to represent actions involving precision gripping is unaffected by chronic limb immobility, then hemiplegic patients’ MI judgments should be equally accurate when based on either the contralesional or ipsilesional limb. Likewise, their performances should be comparable to those of patients in the recovered group.

## Results and Discussion

As illustrated in Figure 6A, there was again no significant difference between hemiplegic and recovered groups ( $F < 1$ ), or between contralesional and ipsilesional hands [ $F(1,6) = 2.5, p = .17$ ] (Table 1). The two-way interaction between group and limb did achieve significance [ $F(1,6) = 6.6, p = .04$ ]. This reflects the fact that hemiplegic patients again showed a tendency to make more accurate decisions based on their paralyzed ( $M = 80.9\%, SD = 14.3$ ) versus ipsilesional limbs ( $M = 55.4\%, SD = 32.4$ ) [ $t(3) = 2.2, p = .12$ ]. Recovered patients showed a trend in the opposite direction: Judgments involving their contralesional limbs ( $M = 74.3\%, SD = 7.2$ ) were less accurate than

those based on their ipsilesional side ( $M = 80.5\%, SD = 11.2$ ) [ $t(3) = 1.6, p = .22$ ].

No differences were observed in RTs for judgments based on the contralesional versus ipsilesional limbs, or between experimental and control groups ( $F < 1.0$ ) in both cases. The interaction between limb and group was, however, significant [ $F(1,6) = 15.0, p = .008$ ]. As illustrated in Figure 6B, currently hemiplegic subjects tended to be slower when decisions were based on their paralyzed ( $M = 3414, SD = 1470$ ) versus ipsilesional ( $M = 2818, SD = 1281$ ) limbs [ $t(3) = 3.1, p = .06$ ], while recovered subjects showed the opposite trend (contralesional,  $M = 3139, SD = 840$ ; ipsilesional,  $M = 2608, SD = 707$ ) [ $t(3) = 2.5, p = .09$ ]. The similarity of this pattern to the group by limb interaction in the accuracy scores suggests the possible contribution of a speed–accuracy tradeoff.



**Figure 6.** Accuracy and speed of precision grip selection. Panel A shows that there was again no significant difference between groups on decisions based on contralesional or ipsilesional limbs. However, hemiplegic patients did tend to perform more accurately for judgments based on the contralesional hand, while control patients showed the opposite trend. Panel B shows that a similar pattern in RTs that may reflect a speed–accuracy tradeoff.

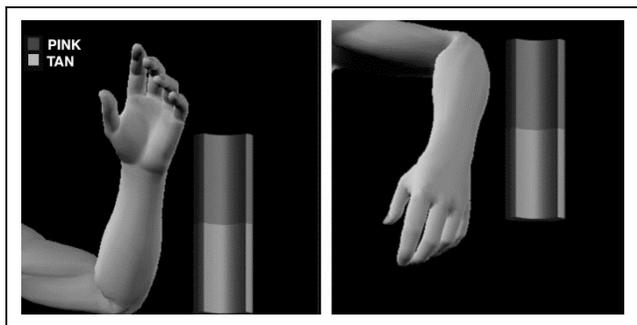
In sum, even in a task that requires internally representing arguably more demanding precision grips, there was again no evidence that chronic limb immobility compromises the integrity of internal action representations. On the contrary, chronically hemiplegic patients tended to perform more accurately when basing decisions on the contralesional side. Likewise, hemiplegic patients performed as accurately and quickly as patients in the recovered group.

In an attempt to determine the generality of these findings to tasks involving other limb segments, a final experiment examines the ability to represent nonprehensile actions involving the upper arm.

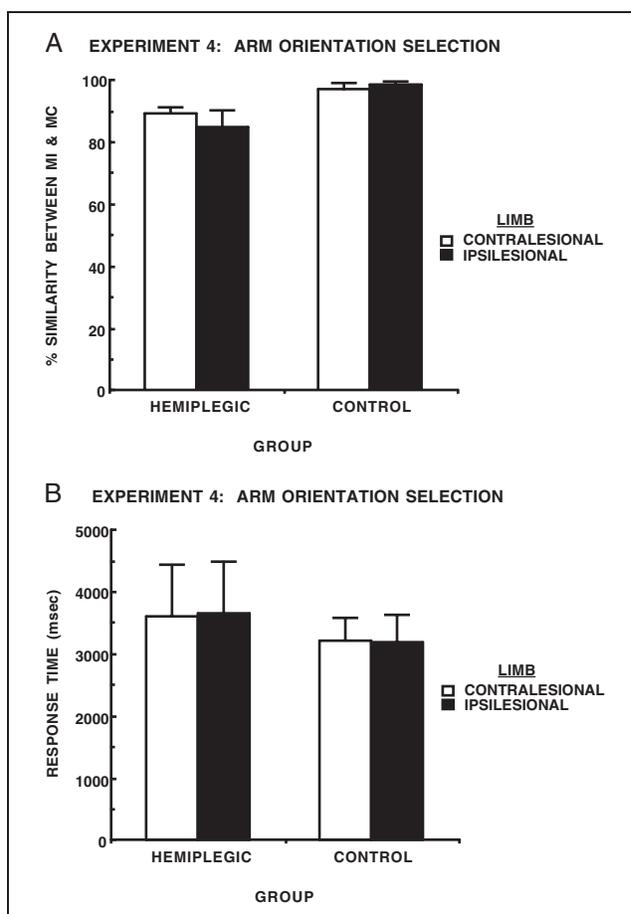
#### EXPERIMENT 4: ARM ORIENTATION SELECTION

An earlier study demonstrated that processes involved in selecting hand grasps are dissociable from those involved in choosing arm postures (Johnson, Corballis, & Gazzaniga, 2001). The latter nonprehensile movements can be evaluated by modifying the power grip selection task used in Experiment 1. As depicted in Figure 7, in the arm orientation selection task, subjects are required to determine which end of the stimulus their elbow would be on if they were to treat the object as an armrest by positioning their forearm in the groove running down the center. Solving this task in a manner consistent with choices in the MC condition involves accurately representing abduction/adduction movements of the upper arm.

If the ability to represent all movements of the paralyzed limb is unaffected by chronic immobility, then—as in the previous three experiments—hemiplegic patients should display no differences in the accuracy of MI judgments between limbs. Further, they should



**Figure 7.** The arm orientation selection task. This task involved determining which end of the stimulus the elbow would be on if the dowel was treated like an armrest, by placing the forearm in the groove running down its length. As in power grip selection, stimuli appeared randomly in eight different picture plane orientations ( $45^\circ$  steps). In the MI condition, subjects reported whether the elbow would be on the pink or tan end. Judgments based on contralesional and ipsilesional limbs were run in separate blocks. In the MC condition, they used the ipsilesional limb to adopt the most natural posture when contacting an actual dowel.



**Figure 8.** Accuracy and speed of arm orientation selection. Panel A shows that both groups performed at an equivalent and high level of accuracy for decisions based on either limb. The control group was more accurate than currently hemiplegic patients. Panel B indicates that this accuracy difference between groups is not attributable to a speed-accuracy tradeoff.

perform as well as those in the recovered group. However, if chronic disuse selectively affects the ability to represent certain actions, specifically those involving the upper arms, then hemiplegic patients' MI decisions based on the paralyzed limb might be less accurate than those involving the ipsilesional side. To the extent that this effect is attributable to chronic disuse, it should only be manifest in results of the currently hemiplegic group.

#### Results and Discussion

As shown in Figure 8A, patients in both groups showed no significant differences in accuracy between limbs ( $F < 1.0$ ) (Table 1). Overall, each group performed at a high level of accuracy. However, in contrast to Experiments 1–3, the currently hemiplegic group ( $M = 87.1$ ,  $SD = 7.4$ ) was significantly less accurate than the recovered group ( $M = 98.0$ ,  $SD = 1.97$ ) [ $F(1,6) = 8.2$ ,  $p = .03$ ]. The interaction between group and limb was not significant [ $F(1,6) = 1.7$ ,  $p = .24$ ]. Figure 8B, indicates that the difference between groups does not

appear to be attributable to a speed–accuracy tradeoff as there was no comparable effect in RT. Likewise, neither the effect of limb, nor the interaction between limb and group attained significance ( $F < 1.0$  in all cases).

Results of this final experiment suggest that the ability to represent nonprehensile movements involving actions of either the contralesional or ipsilesional upper arm may be compromised in chronic hemiplegics relative to controls. This difference could be due either to an effect of chronic limb immobility on the ability to represent actions of either upper arm, or possibly to more generalized deficits in the hemiplegic group as a result of their brain injuries. The latter seems unlikely, however, given that hemiplegics performed as well as controls on all other tasks. Instead, this difference suggests that chronic limb immobility may have differential effects on the ability to represent “certain” actions. Specifically, internal representations of actions involving abduction/adduction of the upper limbs appear to be somewhat “activity dependent.” It should be emphasized, however, that this effect is subtle, as even chronically hemiplegic patients were performing at a high level of accuracy on this task.

Why chronic limb immobility should specifically affect representations of actions involving either the paralyzed or ipsilesional upper arms is unclear. This finding may be related to the fact that movements involving proximal limb segments tend to be more bilaterally represented than distal movements. For instance, a recent fMRI study confirmed that, in addition to effects in the contralateral hemisphere, movements of the shoulder induce increased activation of ipsilateral primary sensorimotor and premotor areas. By contrast, ipsilateral activations only occur in premotor areas during distal finger movements (Nirkko et al., 2001). Therefore, representations of actions involving proximal arm segments may be distributed across both the contralateral and ipsilesional hemispheres. Consequently, it is possible that chronic disuse of one limb may compromise the integrity of representations in both hemispheres. To the extent that these representations contribute to both contralesional and ipsilateral movements of the upper arms, judgments based on either limb might be compromised.

## GENERAL DISCUSSION

The present experiments were motivated by a desire to understand whether internal action representations are affected by chronic limb immobility; that is, whether these representations are activity dependent or independent. Results suggest that both may indeed be true. On the one hand, it was demonstrated that the ability to construct internal action representations of the upper limbs is largely unaffected by chronic hemiparesis. As summarized in Table 1, results of Experiments 1–4 indicate that densely hemiplegic patients are at least as accurate at representing actions involving the paralyzed

limb as those involving the unaffected, ipsilesional, side. Furthermore, on tasks requiring power grip selection (Experiment 1), hand identification (Experiment 2), or precision grip selection (Experiment 3), the accuracy of currently hemiplegic patients did not differ from that of a control group consisting of recovered hemiplegics. This latter finding indicates that the lack of a difference between judgments based on paralyzed versus intact limbs is not due to overall poor performances by hemiplegic patients.

On the other hand, two results indicate that chronic limb disuse may have both negative and positive effects on the ability to internally represent manual actions. Although performing at a high level, currently hemiplegic patients were less accurate than recovered controls when decisions involved representing movements of the proximal segments of either arm (Experiment 4). This finding suggests that the ability to represent nonprehensile actions involving the upper limbs may be mildly compromised by chronic immobility. Conversely, when data were pooled across all four experiments, chronically hemiplegic patients displayed an overall accuracy advantage for MI judgments involving their contralesional ( $M = 85.5$ ,  $SD = 9.2$ ) versus ipsilesional ( $M = 76.5$ ,  $SD = 21.5$ ) limbs [ $t(15) = 2.3$ ,  $p = .036$ ]. For control subjects, the difference between contralesional ( $M = 86.8$ ,  $SD = 11.2$ ) and ipsilesional ( $M = 88.4$ ,  $SD = 9.4$ ) hands was not significant ( $p = .42$ ). All patients tested had experienced hemiplegia of the nondominant hand (Table 1). Therefore, the advantage for representing actions involving the chronically paralyzed, contralesional limb is not related to hand dominance. Further, no such asymmetries were observed in previous studies of acute hemiplegics—who were just beginning rehabilitation training (Johnson, 2000a)—or healthy subjects (Johnson, 2000b). Because the effect was not observed in recovered hemiplegics, it also does not appear related to the physical practice undertaken during extensive post-CVA rehabilitation. Instead, the most tenable explanation for this “hemiplegic advantage” may be that it reflects ongoing implicit and/or explicit imagery of actions involving the paralyzed limb that are presently impossible to undertake. Further tests of this hypothesis are underway.

## Conclusions

While patients with lesions that directly impact parietal and/or premotor areas involved in computing action representations have difficulty representing and executing manual actions (Johnson, 2000a, 2000b; Sirigu et al., 1996), the present findings demonstrate that damage to other cerebral structures can induce a dissociation between the ability to internally represent and overtly undertake such behaviors. Preservation of the ability to represent actions even long after the onset of hemiplegia raises the issue of whether tasks demanding these

processes might have any therapeutic benefits. While the answer to this question remains unclear, it is well known that experiential stimulation is a necessary condition for functional brain reorganization (Nudo, Milliken, et al., 1996; Nudo, Wise, et al., 1996). It is therefore plausible that such tasks may provide an effective means of overcoming the challenging hurdle of how to stimulate brain areas involved in representing actions patients are incapable of producing.

## METHODS

### Subjects

Eight outpatient participants (two women, six men) were selected based on the following criteria: (a) dense hemiplegia (either current or previous) of the nondominant hand resulting from a CVA at least 11 months prior to testing; (b) normal, or near-normal, motor functions in the dominant hand and arm; (c) the ability to comprehend and follow verbal commands; and (d) the ability to provide informed consent. As summarized in Table 2, our experimental group consisted of four chronically hemiplegic outpatients (ID nos. 1–4). Criteria for inclusion in the hemiplegic group included a Brunnstrom Hemiplegia Classification of the contralesional hand as Stage 1 (total flaccidity) or Stage 2 (little or no active finger flexion) (Brunnstrom, 1966). Further, they had to be incapable of contacting the thumb with any one of their digits within a 10-sec period. Conversely, the ipsilesional limb was required to be classified as Brunnstrom Stage 6 (capable of all types of prehension, full voluntary finger extension, and individual finger movements), and patients were required to perform at least three repetitions of sequentially touching each digit to their thumb in a period of 10 sec; that is, a score of 3 on the thumb finger sequencing task (TFST). Contralesional hands of patients in the control group (ID nos. 5–8) were required to be functioning at or

above Brunnstrom Stage 5 (palmar prehension and voluntary mass finger extension), with ipsilesional hands at Stage 6. They were required to complete at least three repetitions of the TFST within 10 sec using the contralesional and ipsilesional hands.

### Procedure

Each subject completed a series of four experiments presented in counterbalanced order across individuals during a single 2.5-hr testing session. The general procedure for the movement selection tasks (Experiments 1, 3, and 4) are outlined here. Methods used in the hand identification task are described below.

In movement selection tasks, subjects performed two conditions: MI—in which they made judgments about how they would engage graphical objects appearing in various orientations without actually moving; and MC—in which they actually performed the required movements in response to nearly identical, 3-D stimulus objects. In order to eliminate the possibility that subjects would rely on memories of responses from the MC task, the MI conditions were always performed first. Prior to beginning the MI conditions, the experimenter demonstrated the required grasp using an actual, 3-D object similar to the one subjects would see depicted on the computer screen.

Stimuli in the MI conditions were photorealistic, graphically rendered objects presented on a Macintosh microcomputer using Superlab software. All MI tasks were preceded by two blocks of practice trials, however, no feedback was provided. Data from these practice trials were not analyzed. Each MI task consisted of eight blocks of trials: four based on the left hand and four based on the right hand presented in alternating order. Identity of the initial block (i.e., left or right hand) was counterbalanced across subjects. Within each block, stimuli were presented in eight

**Table 2.** Summary of Patients Included in the Hemiplegic (ID Nos. 1–4) or Recovered (ID Nos. 5–8) Groups

<i>ID No.</i>	<i>Age</i>	<i>Sex</i>	<i>Time Since CVA (Months)</i>	<i>Lesion Site</i>	<i>Dominant Hand</i>	<i>Brunnstrom Classification Contralesional Limb</i>
1	69	F	12	right periventricular white matter	R	LEFT 1
2	68	F	57	right basal ganglia, internal capsule	R	LEFT 1
3	69	M	59	left basal ganglia	L	RIGHT 1–2
4	64	M	48	right temporal parietal	R	LEFT 1–2
5	73	M	65	right periventricular region frontal lobe	R	LEFT 5
6	65	M	21	right internal capsule/thalamus, caudate	R	LEFT 5–6
7	76	M	12	right internal capsule	R	LEFT 5
8	64	M	23	right anterior cerebral artery distribution, right caudate	R	LEFT 5–6

different orientations: 45° steps around the line of sight axis. These are depicted in figures associated with the individual experiments. Stimuli in each trial were preceded by a 500-msec “Ready!” signal and remained visible until subjects responded by depressing one of two response keys using the index or middle fingers of their ipsilesional hand. Both response preference and response time (RT) were recorded automatically by the computer. Trials were separated by a 1000-msec blank interstimulus interval.

In the MC condition, subjects in both groups used their ipsilesional hands to engage stimulus objects presented in a variety of orientations. Following Johnson (2000b), stimuli were suspended in the center of a black, 60 × 60 cm wooden box that was open at the front so as not to obstruct reaching movements. Stimuli were attached to a horizontally oriented axle that protruded through the back wall of the box. This allowed the experimenter to accurately determine the orientation of the stimulus by observing the relationship between a pointer attached to the axle and degrees mapped on the back of the box. From the subject’s perspective, only the stimulus and the edges of the surrounding box were visible. Subjects were seated in front of the apparatus with their hands resting palms down on designated locations on the table surface. In Experiments 1 and 4, the stimuli were dowels subtending approximately 2.6° × 10.8° of visual angle when viewed from 50 cm. In Experiment 2, widgets used for precision gripping were attached to a platform connected to the axle and subtended 2.6° × 10.8° when seen from 50 cm.

Stimuli for the hand identification task used in Experiment 2 consisted of a set of 10 (five left, five right) photorealistic, canonical hands that were graphically rendered. Within each of the two 60-trial blocks, each hand appeared randomly in six different orientations within the picture plane (60° steps around a full circle). Subjects completed eight practice trials using stimuli that did not appear in actual testing. On each trial, stimulus pictures were preceded by a 500-msec “Ready!” signal and were followed by a 1000-msec blank interstimulus interval. Hands remained visible until subjects responded by pressing either the “left” or “right” response key using the index and middle fingers of their ipsilesional hand.

## Data Analysis

The MI tasks involved deciding what would be the most natural way to grasp objects appearing in different orientations. These tasks do not, therefore, have an objective correct or incorrect answer. Instead, the accuracy of each subject’s imagery performances was evaluated by direct comparison with their preferences exhibited on the companion MC task. Because our hemiplegic subjects were only able to perform the MC

tasks with their uninvolved limbs, imagery judgments based on their paralyzed limbs were compared against predictions of how they would actually grasp stimuli appearing in tested orientations if they were able to do so. For the sake of consistency, this same procedure was used with our control hemiplegic group. To make these predictions, we took advantage of the fact that the two arms and hands obey joint constraints that are 180° out of phase (Mackenzie, 1994). Consequently, if one knows a subject’s grip preferences for a series of stimulus orientations, it is possible to predict those that would be chosen using the opposite arm with near perfect accuracy (Johnson, 2000b). Put differently, for any given stimulus orientation:

$$MC_{\text{left}} = 1/MC_{\text{right}} \quad (1)$$

In this equation,  $MC_{\text{left}}$  and  $MC_{\text{right}}$  refer to the probability of selecting the overhand, or underhand, grip for a specific stimulus using the left or right hand, respectively. In normals, these values are highly correlated ( $R = .99$ ; Johnson, 2000b; Experiment 3). Therefore, inverting functions relating grip preference to stimulus orientation for the ipsilesional limb allows us to accurately predict how hemiplegics would prefer to engage objects if they were able to use the contralesional limb. Movement preferences on the MC tasks for each limb (actual and predicted) can then be directly compared with judgments expressed on the MI tasks to derive a measure of the accuracy of MI. For judgments based on a particular hand ( $k$ ) and a stimulus appearing in a particular orientation ( $\theta_i$ ):

$$\text{Accuracy MI } \theta_{ik} = 100(1 - |MI \theta_{ik} - MC \theta_{ik}|) \quad (2)$$

In each movement selection experiment, these accuracy scores were computed separately for each subject’s MI performances based on the contralesional and ipsilesional limbs. As detailed separately for each experiment, these mean accuracy scores were then submitted to repeated-measures ANOVAs to evaluate differences between hands and/or groups in each experiment. Likewise, repeated-measures ANOVAs were performed on RT data from MI conditions to evaluate potential speed–accuracy tradeoffs. RTs less than 300 msec in duration, or greater than 2  $SD$ ’s from the mean for each subject and each hand were identified as outliers and eliminated prior to RT analysis (<2.0% of responses).

For the hand identification task (Experiment 2), the percentages of correct responses to pictures depicting each subject’s contralesional versus ipsilesional hand were computed. These values were submitted to 2 (Hand) × 2 (Group) repeated-measures ANOVAs. RTs from correct trials were selectively averaged to yield means reflecting the amount of time each subject required to correctly identify pictures depicting their involved versus uninvolved hand. As with accuracy data,

these means were then submitted to repeated  $2 \times 2$  ANOVA after eliminating outliers as described above for the movement selection tasks. Fewer than 2% of trials were identified as outliers.

### Power Analyses

Due to the relatively small number of cases, it can be argued that these statistical tests lack the power necessary to detect potentially important differences between groups and/or limbs. The fact that we did detect a significant difference in the arm orientation selection task argues against this claim. Nevertheless, we performed power analyses for ANOVA main effects of group (hemiplegic vs. recovered) and limb (contralateral vs. ipsilateral), assuming a significance level  $\alpha = .05$ . The power of a statistical test is the probability of rejecting the null hypothesis when it is, in fact, false. Given our relatively small sample size of eight cases, these analyses suggest that we should be able to detect medium to large effects with reasonable power. Specifically, the  $F$  test of the difference between limb, to which all eight subjects contributed, would detect a large effect ( $\Delta = 1.25$ ) with high power (0.92), and a medium effect ( $\Delta = .75$ ) with moderate power (0.54). The  $F$  test of the difference between groups was able to detect a large effect ( $\Delta = 1.25$ ) with a moderate power (0.63), and a medium effect ( $\Delta = .75$ ) with low power (0.28) (Cohen, 1988).

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Reprint requests should be sent to Scott H. Johnson, Center for Cognitive Neuroscience, 6162 Moore Hall, Dartmouth College, Hanover, NH 03755-3569, USA, or via e-mail: scott.h.johnson@dartmouth.edu.

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