A Dissociation between the Representation of Tool-use Skills and Hand Dominance: Insights from Left- and Right-handed Callosotomy Patients

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Abstract

■ The overwhelming majority of evidence indicates that the left cerebral hemisphere of right-handed humans is dominant both for manual control and the representation of acquired skills, including tool use. It is, however, unclear whether these functions involve common or dissociable mechanisms. Here we demonstrate that the disconnected left hemispheres of both right- and left-handed split-brain patients are specialized for representing acquired tool-use skills. When required to pantomime actions associated with familiar tools (Experiment 2), both patients show a right-hand (left hemisphere) advantage in response to tool names, pictures, and actual objects. Accuracy decreases as stimuli become increasingly symbolic when using the left hand (right hemisphere). Tested in isolation with lateralized pictures (Experiment 3), each patient's left hemisphere demonstrates a significant advantage over the right hemisphere for pantomiming tool-use actions with the contralateral hand. The fact that this asymmetry occurs even in a left-handed patient suggests that the left hemisphere specialization for representing praxis skills can be dissociated from mechanisms involved in hand dominance located in the right hemisphere. This effect is not attributable to differences at the conceptual level, as the left and right hemispheres are equally and highly competent at associating tools with observed pantomimes (Experiment 4). ■

INTRODUCTION

With few exceptions, over a century of research indicates that the left cerebral hemisphere of right-handed humans is specialized for both motor control and the representation of acquired manual skills (i.e., praxis) including tool use. Unilateral damage to the left, but rarely the right (Raymer et al., 1999; Marchetti & Della Sala, 1997), cerebral hemisphere is associated with ideomotor apraxia (IM), a deficit in praxis that cannot be attributed to elementary motor or perceptual deficits. IM patients have difficulties performing one or more of the following acts even when using the ipsilesional hand: pantomiming tool and/or non-tool-use actions, gesturing to verbal command, imitating movements, and in some instances, actually using tools (Leiguarda & Marsden, 2000). In addition, functional neuroimaging studies have identified specific regions of the left hemispheres of healthy adults that are active in association with tasks involving tools and/or tool-use actions (Johnson-Frey, 2004).

A fundamental yet unresolved question concerns the relationship between acquired praxis and hand dominance. On the one hand, it is possible that the same mechanisms account for both the representation of skills and hand preferences. For example, right hand dominance might reflect the existence of a left-lateralized system for representing praxis (Heilman, 1997; Geschwind & Galaburda, 1985), possibly in parietal cortex (Johnson-Frey, 2004; Heilman, Rothi, & Valenstein, 1982). This would allow these representations to be accessed directly by frontal areas in the left hemisphere that are involved in controlling distal movements of the contralateral right hand. Following this logic, left-handers should represent praxic skills in their motor dominant right hemispheres. Consistent with this perspective are several case reports of crossed apraxia in which unilateral right hemisphere lesions cause IM in left-handers (Dobato et al., 2001; Poeck & Lehmkuhl, 1980; Valenstein & Heilman, 1979; Heilman, Coyle, Gonyea, & Geschwind, 1973; Poeck & Kerschensteiner, 1971). On the other hand, there are also reasons to believe that although processes responsible for hand dominance and the representation of acquired skills typically reside in the left cerebral hemisphere, they may actually involve dissociable mechanisms. A relatively small number of right-handed patients with right hemisphere lesions manifest crossed apraxia (Raymer et al., 1999; Marchetti & Della Sala, 1997). Moreover, a study

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of 90 adults undergoing amobarbital-induced unilateral inactivation of the cerebral hemispheres indicates that the ability to pantomime actions is more closely associated with laterality of language functions rather than hand dominance (Meador et al., 1999).

An important source of evidence on the relationship between handedness and skill representations comes from studies of IM in patients with damage to the corpus callosum, the so-called callosal apraxics (Buxbaum, Schwartz, Coslett, & Carew, 1995; Graff-Radford, Welsh, & Godersky, 1987; Watson & Heilman, 1983; Geschwind, 1965; Geschwind & Kaplan, 1962). In right-handed patients, callosal damage typically results in apraxia with the left hand; a finding that has long been attributed to a disconnection between left hemisphere sensorimotor centers and areas of the right hemisphere necessary for left hand motor control (Goldenberg, 2003; Liepmann, 1907). Yet, there appear to be exceptions. Perhaps the most oft-cited case of IM, Liepmann's ''imperial counselor,'' was a largely right-handed individual with apraxia of the dominant limb following damage to the anterior two thirds of his corpus callosum and subcortical cysts in the left cerebral hemisphere (Goldenberg, 2003; Liepmann, 1905).

Unfortunately, very little data exist on callosal apraxia in left-handers. At least one left-handed patient with a naturally occurring callosal lesion is reported to have left hand IM to verbal command (Lausberg, Gottert, Munssinger, Boegner, & Marx, 1999). This is consistent with a disconnection between left-hemisphere praxic representations and mechanisms responsible for hand dominance located in the right hemisphere (Lausberg et al., 1999). There are, however, several factors that might be contributing to these observations. It is unclear to what extent damage noted in the white matter of left parietal cortex is involved, as deep lesions in this region are sometimes associated with IM (Basso, Faglioni, & Luzzatti, 1985). There also appear to be some spared fibers in the splenium that could enable interhemisphere communication.

Additionally, data from studies of right-handed patients who have undergone surgical transactions of the corpus callosum have been somewhat inconsistent with regard to the laterality of praxis representations. Consistent with a verbal–motor disconnection, several studies only report apraxia of the left hand when movements are cued by verbal commands (Zaidel & Sperry, 1977; Gazzaniga, Bogen, & Sperry, 1967; Geschwind & Kaplan, 1962), suggesting that the right hemisphere can control manual skills in response to nonlinguistic cues. By contrast, a recent investigation demonstrates left hand apraxia in three callosotomy patients even when skills are pantomimed in response to objects presented in central vision (Lausberg, Cruz, Kita, Zaidel, & Ptito, 2003).

In an attempt to clarify the relationship between mechanisms responsible for praxis and hand dominance, we investigated the organization of tool-use actions in left- and right-handed callosotomy patients. Unlike patients with vascular lesions, both individuals have precisely the same damage-complete surgical resection of the corpus callosum, in the absence of any collateral damage to other structures as verified by magnetic resonance imaging (MRI). Despite their differences in hand dominance, both patients have left hemisphere language dominance as verified by presurgical Wada testing. In contrast to IM patients with unilateral brain injuries, neither hand has impaired motor functions, enabling each subject to serve as his/her own control (for further details see Method section). In Experiment 1, we investigated their abilities to demonstrate tool-use gestures with the actual objects in hand. Experiment 2 compared the accuracy of tool-use pantomime in response to stimuli ranging from concrete (actual tools) to moderately symbolic (line drawings of tools) to highly abstract (verbal names of tools). Unlike previous studies, Experiment 3 used the divided visual field technique to test the representation of tool-use skills in the isolated cerebral hemispheres independently. Finally, in Experiment 4, this technique was used to evaluate the ability of each hemisphere to associate observed tool-use gestures with appropriate tools (i.e., gesture identification).

Hypotheses

We reasoned that two patterns might emerge across these studies depending on the relationship between mechanisms involved in hand dominance and praxis. If tool-use skills are represented in the motor-dominant hemisphere, then these patients should show opposite patterns: The right-handed patient J.W. should be at a disadvantage when using his left hand as a result of a disconnection between left hemisphere areas representing tool-use skills and contralateral, right hemisphere motor areas. By contrast, the left-handed patient V.J. should be at a disadvantage when using her right hand, because praxis representations in her right hemisphere are disconnected from contralateral motor centers in her left hemisphere. Alternatively, it is possible that the left hemisphere is dominant for representing praxis regardless of one's hand dominance (i.e., that praxis representations are dissociable from mechanisms responsible for handedness). If so, then both patients should perform very similarly: Regardless of their hand dominance J.W. and V.J. should be at a disadvantage with the left hand due to a disconnection between left hemisphere praxis representations and contralateral right hemisphere motor areas.

EXPERIMENT 1: DEMONSTRATING TOOL USE

Apraxic patients typically perform much worse when they are required to pantomime tool-use actions as compared with using actual tools (Leiguarda & Marsden, 2000). This finding is often interpreted as a failure to perform volitional actions from memory without external support (Rothi & Heilman, 1997). Yet, many IM patients with left hemisphere lesions are known to also make errors when demonstrating how tools are used with the actual objects in hand (De Renzi, Faglioni, & Sorgato, 1982) and even when using tools in natural contexts (Goldenberg & Hagmann, 1998; Clark et al., 1994).

To establish a baseline against which subsequent pantomime performances can be framed, we asked our patients to demonstrate how each of the 24 familiar tools would normally be used. Based on recent findings in three right-handed callosotomy patients (Lausberg et al., 2003), our expectation was that performances on this task would be at or near ceiling. To the extent that any errors were observed, we reasoned that they would take one of two forms. If skill representations and hand dominance co-occur in the motor-dominant hemisphere, then patients might simply perform better with their preferred hand. Alternatively, if the left hemisphere is specialized for representing tool-use skills regardless of handedness, then both left- and right-handed patients should show an advantage when performing with the right hand.

Results and Discussion

As expected, overall accuracy was quite high; both patients were at 100% with their right hands. Nevertheless, left-handed patient V.J. performed less accurately with her dominant left hand (87%), $t(22) = 2.1, p < .05$. A similar trend was also observed in right-handed patient J.W. (95%), although it did not reach significance ($p = .10$).

The results of patient J.W. are generally consistent with those reported by Lausberg et al. (2003) in showing that right-handed callosotomy patients perform accurately when demonstrating how familiar tools are used with either hand. By contrast, left-handed patient V.J. experienced some difficulties when demonstrating how tools are used with her dominant left hand. The fact that V.J. actually performed better with her non-dominant right hand may seem paradoxical given that she has always been left-handed and continues to use tools with her left hand in everyday life. However, this finding makes sense if her left nonmotor-dominant hemisphere is specialized for the representation of tool-use skills. As a result of her surgery, it is no longer possible for information to be transferred between the cerebral hemispheres. Consequently, tool-use representations in her left hemisphere would not be directly accessible by dominant motor centers in the right hemisphere that are used to control distal movements of the left hand. This is revealed when she is tested on the object use task that, unlike naturalistic tool use, is comparatively devoid of contextual information (Schwartz, 1997). For example, although subjects were required to demonstrate how a hammer is used, they did so without actually pounding a nail into a board. This task may therefore place more demands on memory than naturalistic tool use, while providing considerably less structural and semantic information. In short, these initial observations are consistent with a dissociation between mechanisms responsible for representing praxis skills and those involved in hand dominance.

EXPERIMENT 2: TOOL-USE GESTURE TO VERBAL, PICTORIAL, AND OBJECT CUES

As argued by Geschwind and Kaplan (1962), the typical right hand advantage for pantomimes to verbal command by callosal apraxics may reflect a disconnection between left hemisphere language centers and motor areas in the right hemisphere necessary to control the left hand (Volpe, Sidtis, Holtzman, Wilson, & Gazzaniga, 1982; Brion & Jedynak, 1972). If left hand IM results from a verbal–motor disconnection, then patients should perform more accurately when cued by nonverbal stimuli (pictures and objects). Alternatively, if left hand IM reflects a disconnection between praxis representations in the left hemisphere and motor centers in the right, then left IM should persist even when nonverbal stimuli are used, as was recently observed in a series of three right-handed, callosotomy patients (Lausberg et al., 2003). To evaluate these possibilities in the context of both right- and left-handedness, we compared the accuracy of pantomimes made in response to verbal (tool names), pictorial (line drawings of tools), and object (actual tools) cues. This design allowed us not only to determine the relationship between hand dominance and tool-use gesture in response to verbal versus nonverbal cues, but to also assess how performances are affected as action cues become increasingly symbolic, progressing from the actual tools themselves to line drawings to verbal names. Given the well-established superiority of the left cerebral hemisphere for processing symbolic representations (Gazzaniga, 2000), effects of this manipulation might be most pronounced when using the left hand (i.e., right hemisphere).

Results and Discussion

Consistent with tool-use demonstration, Figure 1 shows that both V.J., $F(1,23) = 35.9, p < .00001, MSE = .71$, and J.W., $F(1,23) = 15.5, p = .0007, MSE = 1.11$, performed more accurately across all tasks when using their right hands. In addition, single degree of freedom linear contrasts revealed that both the left- and right-handed patients' accuracy with their left hands decreased as stimulus items became increasingly abstract (i.e., progressed from objects to pictures to names), $F(1,23) = 7.4, p = .01, MSE = .64$, and $F(1,23) = 4.2, p = .05, MSE = .71$, respectively.

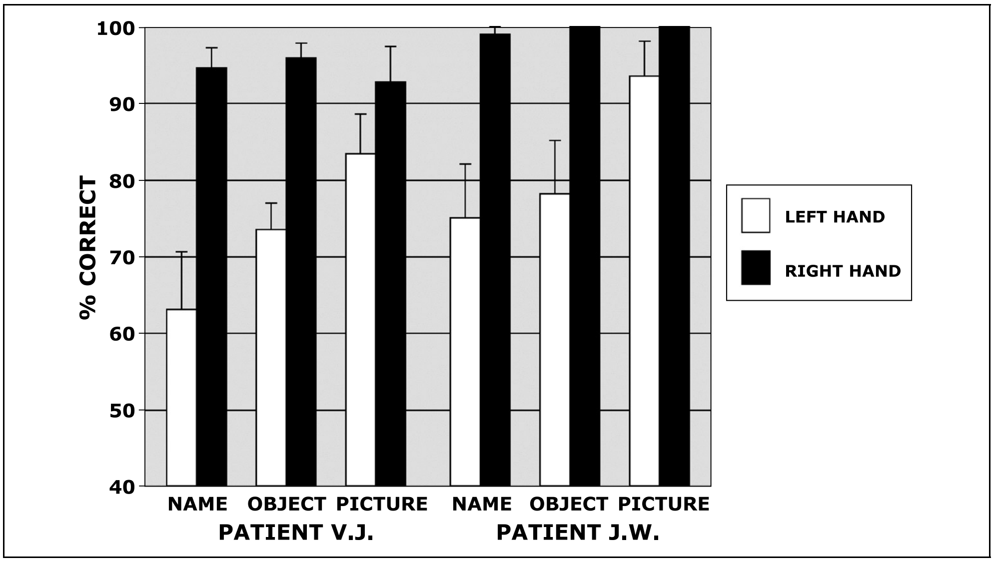

Figure 1. Right hand advantage for production of tool-use actions by left- and right-handed callosotomy patients to centralized stimuli. Both left- and right-handed patients demonstrate a mean advantage when executing tool-use pantomimes with the right hand in response to verbal cues (tool names, NAMES), visual presentation of actual tools (OBJECT), and line drawings (PICTURE). This suggests that the left cerebral hemisphere is specialized for representing tool-use actions regardless of cerebral dominance for motor control. Error bars here and in Figure 3 represent within subject *SE*s.

In sum, three interesting results emerged from this experiment. First, regardless of the type of cue involved, both our left- and right-handed callosotomy patients performed tool-use gestures more accurately with their right hands. This is inconsistent with the language–motor disconnection hypothesis, according to which they should only have showed impaired left hand performances for verbal stimuli and not for pictures and objects. Instead, this result is consistent with Experiment 1 in suggesting that both patients' left hemispheres are specialized for the representations of praxis. Second, the fact that this right hand advantage is observed in the left-handed patient V.J. is further evidence that mechanisms involved in representing these skills are dissociable from processes in the right hemisphere responsible for her hand dominance. Third, when pantomiming with their left hands (right hemispheres), both patients' error rates increased as stimuli became more symbolic. This is true even when these symbolic cues are nonlinguistic (i.e., line drawings). In fact, the accuracy of left hand performances of both patients did not differ significantly between verbal and pictorial cues ($p > .20$ in both cases).

EXPERIMENT 3: PANTOMIME TO LATERALIZED PICTORIAL CUES

Whereas hand movements are controlled predominantly by the contralateral hemisphere, a minority of descending motor pathways that do not cross the pyramidal decussation enable some degree of ipsilateral control (Brinkman & Kuypers, 1973). Because stimuli were perceptually available to both cerebral hemispheres in Experiments 1 and 2, it is possible that ipsilateral motor control may be partly responsible for more accurate pantomime production with the right hand. This is of particular concern for V.J. whose right hemisphere is motor dominant. To eliminate this possibility, a third experiment used the divided visual technique to present line drawings of the 24 tools to the left or right cerebral hemispheres exclusively. A recent study by Goldenberg, Laimgruber, and Hermsdorfer (2001) used a similar procedure to evaluate praxis in a right-handed patient with partial destruction of the corpus callosum and limited subcortical damage. Consistent with a left hemisphere specialization for skilled praxis, the critical comparison revealed a substantial advantage when pictures were presented to the right visual field (left hemisphere) and gestures were produced with the right hand versus when cues were exposed to the left visual field (right hemisphere) and gestures were produced with the left hand. It is of interest to determine whether patients with complete surgical disconnection, and in the case of V.J., left-handedness, also show this pattern. If so, then it would be strong evidence that, as suggested by the results of Experiments 1 and 2, the left hemisphere is indeed specialized for representing tool-use skills regardless of hand dominance. In addition, 8 healthy control subjects (4 left-handed and 4 right-handed) were tested to provide normative data. Given their ability to rapidly transfer information between the cerebral hemispheres via the intact corpus callosum, we did not expect controls to show any differences between conditions.

Results and Discussion

As anticipated, control subjects were highly accurate across all conditions. No effects reached conventional levels of significance ($p > .10$ in all cases). By contrast, Figure 2 shows that patients were significantly less accurate than controls, $F(1,8) = 30.5$, $p < .00001$, $MSE = .065$. Both J.W., $F(1,23) = 37.3$, $p = .00003$, $MSE = 1.2$, and V.J., $F(1,23) = 17.8$, $p = .003$, $MSE = 1.7$, performed better when stimuli were presented to the visual field ipsilateral to the response hand. This was expected because under these conditions, the hemisphere that had access to the visual stimulus also controlled the response hand. More importantly, both J.W., $t(23) = 2.4$, $p = .02$, and V.J., $t(23) = 4.47$, $p = .0002$, performed best when stimuli were presented in their right visual fields (left hemispheres) and actions were produced with their right hands versus when stimuli were presented to their left visual fields (right hemispheres) and responses were made with their left hands (see Figure 2).

The persistence of a left hemisphere/right hand advantage under divided visual field testing is strong evidence that the right hand advantage for tool-use gesture is not attributable to influences of the ipsilateral right hemisphere. Instead, the findings of Experiments 1–3 converge on the hypothesis that hand dominance and the representation of praxis skills involve dissociable mechanisms (Lausberg et al., 1999; Raymer et al., 1999). In J.W., the mechanism(s) for representing tool-use skills reside(s) within the left hemisphere as do the motor areas that control movements of his dominant hand. Consequently, pantomimes are most accurate when stimuli are presented to the right visual field/left hemisphere and actions are performed with the right hand. Critically, this same asymmetry is evident in V.J. who acquired and continues to practice these tool-use skills in everyday life using her left hand. This asymmetry in performance is consistent with a disconnection between the left hemisphere system that represents tool-use skills (Johnson-Frey, 2003, 2004; Johnson-Frey & Grafton, 2003) and right hemisphere motor areas that control her dominant left hand.

If this is the case, then why does V.J. succeed at everyday unimanual tool use with her left hand? As noted earlier, it is well established that apraxic symptoms are diminished or absent when patients are allowed to actually use tools in naturalistic contexts. Moreover, although at a disadvantage relative to the left, the results of Experiment 2 indicate that the right hemisphere is capable of controlling tool-use gestures particularly in response to concrete nonsymbolic cues of the sort involved in naturalistic tool use. These facts, together with her longstanding right hemisphere dominance for motor control likely account for her ongoing left-hand preference in these activities.

In both patients, performance with the left hand was relatively poor regardless of the visual field to which stimuli were presented. We interpret this as reflecting the fact that control of the left hand is accomplished by the right hemisphere, which is isolated from visuokinesthetic representations of tool-use skills located in the left hemisphere (Heilman et al., 1982). Therefore, even when visual stimuli are presented directly to the left visual field, the right hemisphere has difficulty accessing the representations necessary for accurate pantomime with the left hand. When stimuli are presented to the right visual field (left hemisphere), these representations are accessed but cannot be effectively transferred to the right hemisphere motor centers that control the left hand's performance. Likewise, both individuals exhibit their worst performances when stimuli are presented to the left visual field (right hemisphere) and performances are executed with the right hand. In this case, the right hemisphere is unable to access accurately the left hemisphere praxis system and does not have access to motor regions necessary to initiate and control movements of the right hand.

Finally, although the right hemisphere appears to be at a relative disadvantage it is still capable of accessing and controlling tool-use gestures with the left hand to a limited extent. This is consistent with earlier observations in patients with callosal apraxia (Lausberg et al., 2003; et al., 2001). The mechanisms that could be responsible for this effect are discussed below.

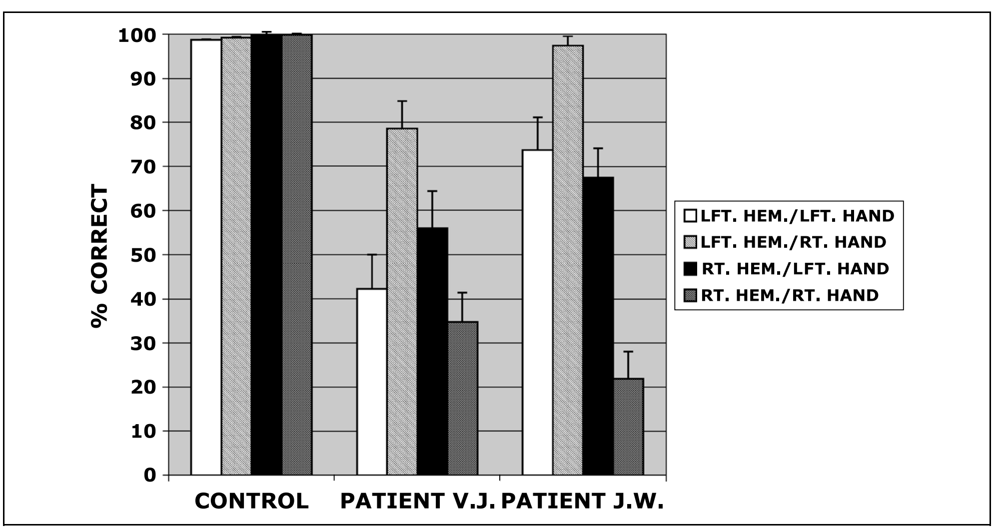

Figure 2. Right-hand advantage for production of tool-use actions by left- and right-handed callosotomy patients to stimuli under divided visual field conditions. When the divided visual field technique is used to present pictures of tools to the left and right hemispheres in isolation, both hemispheres perform poorly with the ipsilateral hands. However, the left hemispheres of both patients demonstrate an advantage for executing tool-use actions with the contralateral hands.

EXPERIMENT 4: IDENTIFICATION OF TOOL-USE GESTURES

There is one final possibility that could account for the left hemisphere–right hand advantage shown by our left-handed patient on pantomime production tasks: Perhaps both hemispheres represent praxis skills, but the right hemisphere is impaired at forming the correct association between a tool and the appropriate action. This has been referred to in the literature as *conceptual apraxia* (Ochipa, Rothi, & Heilman, 1992) and involves mechanisms dissociable from those needed for skill production (Ochipa, Rothi, & Heilman, 1989b). To evaluate this alternative, patients performed a gesture identification task in which they observed movies of an actor pantomiming tool-use gestures and were then required to select from among two line drawings the one depicting the associated tool. The key to this procedure is that on each trial, the divided visual field technique was used to present both line drawings to either the left or right visual fields selectively. If the right hemisphere is impaired at conceptualizing associations between tools and associated actions, then the pattern of results here should look similar to those observed in Experiment 3, that is, there should be an advantage when tools are presented to the right visual field (left hemisphere) and responses are made with the right hand versus when they are presented to the left visual field (right hemisphere) and responses are made by the left hand. By contrast, if both hemispheres are able to correctly form associations between tools and actions, then they should perform comparably. Again, normative data were acquired from 8 healthy adults (4 left-handed and 4 right-handed).

Results and Discussion

Figure 3 shows that patients were again at a disadvantage relative to healthy controls, $F(1,6) = 272.4265$, $p < .00001$, $MSE = 1.3$, and control subjects showed no significant differences in performances between conditions ($p > .10$ in all cases). Yet, despite having substantial difficulties producing actions in response to the very same pictorial stimuli in Experiments 2 and 3, each patient's right hemisphere performed remarkably well in this task. No significant differences were observed between hemispheres or hands for either J.W. or V.J. ($p > .24$ in all cases).

In short, although the left hemisphere appears to be dominant for representing movements involved in tool-use skills, these findings suggest that the ability to conceptualize associations between tools and actions can be accomplished bilaterally. This is consistent with observations that conceptual apraxia can arise from damage to either or both cerebral hemispheres (Ochipa et al., 1992; Ochipa, Rothi, & Heilman, 1989a; De Renzi & Lucchelli, 1988). A relatively preserved ability to discriminate between observed gestures in the face of impaired production has also been observed in aphasic patients (Vaina, Goodglass, & Daltroy, 1995; Bell, 1994; Varney & Damasio, 1987; Heilman et al., 1982). Heilman et al. (1982) suggest that these patients may also demonstrate IM due to a disconnection between intact skill representations (visuo-kinesthetic engrams) located in left parietal regions and left frontal regions necessary for motor programming. Our findings suggest instead that gesture production and recognition may be mediated by distinct representational systems, with the latter being represented bilaterally in the cerebral hemispheres.

Importantly, this demonstrates that the left hemisphere–right hand advantage for gesture production in both J.W. and V.J. (Experiments 1–3) cannot be explained by difficulties of the right hemisphere in forming the correct associations between tool stimuli and the actions involved in their usage.

GENERAL DISCUSSION

The goal of this work was to elucidate the relationship between mechanisms involved in representing praxis,

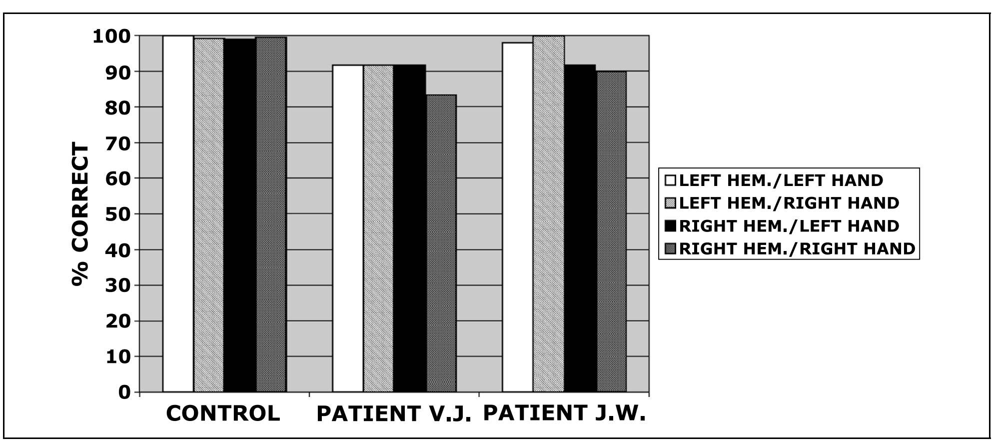

Figure 3. Equivalent performance between hemispheres of action comprehension task by left- and right-handed callosotomy patients under divided visual field conditions. In contrast to action production, both left and right cerebral hemispheres are equal and highly competent at identifying tools associated with actions pantomimed by another individual.

specifically tool use, and those responsible for hand dominance. Our results consistently indicate that these mechanisms can be dissociated. Specifically, we have presented evidence of left hemisphere dominance in the representation of tool-use skills in a left-handed callosotomy patient with no other apparent brain damage. Although patient V.J. does show the typical left hemisphere dominance for language (see details in Methods), this finding cannot be dismissed as verbal–motor disconnection because it is observed even when tool-use actions are cued with nonverbal stimuli (Experiments 1–3). Moreover, it does not appear to reflect ipsilateral control by the motor dominant right hemisphere, as it persists even when stimuli are only made available to the left cerebral hemisphere (Experiment 3). Nor can it be accounted for by a failure of the right hemisphere to form correct associations between tools and actions (Experiment 4). The fact that a left hemisphere advantage for praxis skills is observed even in a patient who acquired and continues to perform unilateral tool-use behaviors with her left hand strongly suggests that this may reflect endogenous asymmetry not unlike that of language. Although the source of this specialization is unknown, left hemisphere dominance for praxis skills may reflect an asymmetry for constructing symbolic representations. The fact that both J.W. and V.J. performed less accurately when gesturing in response to increasingly symbolic cues with their left hands (right hemispheres) is consistent with this interpretation (Experiment 2). The left hemisphere specialization for complex sequencing and timing operations, upon which both language production and skilled praxis depend, may also contribute to these effects (Harrington & Haaland, 1991; Lomas, 1976; Kimura & Archibald, 1974).

Our results are consistent with those from an earlier report of left-handed IM in a patient following damage extending the full length of the corpus callosum (Lausberg et al., 1999). Whether this organization is typical of left-handers is an empirical question that is currently being addressed in our laboratory through functional neuroimaging studies. As noted earlier, at least some left-handers appear to develop IM following right hemisphere lesions (Dobato et al., 2001; Poeck & Lehmkuhl, 1980; Valenstein & Heilman, 1979; Heilman et al., 1973; Poeck & Kerschensteiner, 1971). This suggests that there may be variations in the laterality of skill representations across this population. Here we have chosen to focus on transitive skills. It remains an open question whether intransitive skills (e.g., waving goodbye) are also represented predominantly in the left cerebral hemisphere or whether these actions are represented bilaterally (Rapcsak, Ochipa, Beeson, & Rubens, 1993).

Lastly, it is noteworthy that even when tested in isolation (Experiment 3), the right cerebral hemispheres of both J.W. (67.5%) and V.J. (56%) display some ability to access and produce tool-use gestures with the left hand. This may indicate that the right hemisphere does have a system for representing praxis that may, under more ordinary circumstances, be subordinate to the left. As shown in Experiment 4, the right hemisphere does appear to have access to representations necessary for recognizing tool-use gestures, and it is possible that these can be used to guide praxis with modest accuracy. Alternatively, it is also possible that some information is being transferred from the left to the right hemisphere subcortically, or that the left hemisphere is able to influence performance vis-à-vis cross cuing during gesture production. Additional work will be needed to differentiate between these possibilities.

As with any methodology for investigating structure–function relationships, the use of brain-injured patients encounters certain limitations. A key point is that our goal in taking this approach was not to make broad generalizations regarding population-level brain organization. This is better accomplished through other techniques that allow investigation of larger samples of healthy individuals. Instead, we sought to determine if it is possible to functionally dissociate mechanisms responsible for hand dominance and praxis and have shown that this is indeed the case. The choice to use split-brain patients in particular was motivated by evidence that the presence of an intact corpus callosum can mask the specific contributions of each hemisphere and of any subcortical pathways during motor tasks (Kennerley, Diedrichsen, Hazeltine, Semjen, & Ivry, 2002; Iacoboni, Ptito, Weekes, & Zaidel, 2000). It is noteworthy that our results are consistent with existing functional MRI data demonstrating left hemisphere dominance for tool-use gestures in right-handers (Choi et al., 2001; Moll et al., 2000; Johnson-Frey, Newman-Norlund, & Grafton, in press). A more detailed investigation of left-handers in currently underway in our laboratory.

A final issue specific to our choice of these two individuals is that in addition to opposite motor dominance, they show slightly different patterns of lateralization of language and writing functions. As detailed in the Methods section, V.J.'s right hemisphere appears to have some linguistic abilities including lexical decision and letter writing. Rather than a drawback, however, we view these individual differences as valuable in revealing general patterns of hemispheric specialization. In the context of these differences, the consistent finding of left hemisphere dominance for the representation of tool-use skills can more easily be attributed to general functional differences rather than to idiosyncratic sources.

METHODS

Callosotomy Patients

Consent was obtained according to the Declaration of Helsinki and was approved by the Committee for the

Protection of Human Subjects at Dartmouth College. Callosotomy patients J.W. and V.J. participated in this study. Both J.W. and V.J. completed high school and have IQ's within the normal range. Presurgical Wada testing demonstrated that both patients have left hemisphere language dominance. Postsurgical MRI indicates that both patients neither have any extracallosal brain damage nor apparent sparing of callosal fibers. Hand dominance was established using the Edinburgh Handedness Inventory (Oldfield, 1971). J.W. and V.J indicated right- and left-hand preferences for all items, respectively.

Patient J.W. is a strongly right-handed man who was 48 years old at the time of testing. At the age of 25, he underwent a two-stage resection of the corpus callosum for relief of intractable epilepsy (for a case history, see Gazzaniga, Smylie, Baynes, Hirst, & McCleary, 1984). Postsurgical MRI confirmed that his corpus callosum was fully severed (Gazzaniga, Holtzman, Deck, & Lee, 1985). Although J.W. is left-hemisphere dominant for language, his right hemisphere does possess a lexicon (Sidtis, Volpe, Holtzman, Wilson, & Gazzaniga, 1981; Sidtis, Volpe, Wilson, Rayport, & Gazzaniga, 1981) and rudimentary syntactic comprehension (Baynes & Gazzaniga, 1988). The linguistic abilities in his right hemisphere, however, are not nearly as well developed as those of his left hemisphere (Gazzaniga & Smylie, 1984; Gazzaniga et al., 1984). One study suggested that several years after his callosotomy, his right hemisphere developed the ability to generate speech (Baynes, Wessinger, Fendrich, & Gazzaniga, 1995). Follow-up testing, however, has failed to find further evidence for right hemisphere speech.

Patient V.J. is a 49-year-old left-handed woman. Her mother, her only sister, and her only daughter are also left-handed. She underwent a two-stage callosotomy at the age of 42. Presurgical Wada testing and postsurgical lateralized behavioral testing are consistent with left-hemisphere language dominance, but like J.W., V.J. does have some linguistic abilities in her right hemisphere, such as lexical decision (Baynes et al., 1998). In addition, it has been suggested that her right hemisphere may play a unique role in writing (Baynes et al., 1998). Although her right hemisphere is unable to generate verbal or written language, it does possess a modular motor program that results in an ability to produce letters with her left hand. There is no evidence that this motor program exists in her left hemisphere because she cannot write letters with her right hand. This right hemisphere writing module does not seem to be associated with any other linguistic abilities in the right hemisphere.

Healthy Controls

Eight healthy control subjects (mean age = 29 years, range = 22–54 years) were also tested in Experiments 3 and 4. None had a history of neurological or psychiatric illness, and all were naïve to the hypotheses under investigation. As determined by the Edinburgh Handedness Inventory and self-report, 4 (1 man and 3 women) were left-hand-dominant and the remaining (1 man and 3 women) 4 were right-hand-dominant.

Stimuli

As listed in the Appendix, 24 common tools associated with unilateral manual actions by the dominant hand were selected from a normative battery of objects (Snodgrass & Vanderwart, 1980). These same items were used in all experiments as described below, but the manner in which they were cued (verbal naming, displaying the actual object, or displaying a line drawing) differed depending on the task. Details of the experimental procedures and data analyses unique to each experiment are provided below.

Experiment 1

Procedure

Each object was placed on the table directly in front of the subject in random order. On every trial, subjects were instructed to grasp the object and demonstrate as accurately as possible how it would normally be used. Both subjects performed two blocks, one with the left hand and another with the right hand, beginning with their dominant hand.

Analysis

Pantomimes were video recorded from an angle oblique to the subjects' midlines and scored off-line by two trained raters. Following previous investigators, a distinction was made between conceptual and execution errors (Heilman & Rothi, 1997). Conceptual errors were those in which either no recognizable response was made or an incorrect action was performed. Two types of execution errors were coded: motion errors in which the hand was shaped appropriately to engage the object but the movements of the limb were incorrect for its use and hand shape errors in which the movements of the limb were correct but the hand was not shaped appropriately for the object. Each pantomime was assigned a total score on a scale of 0–4 points. Pantomimes that were conceptually correct were assigned 2 points. One additional point was added if the motion was correct and another if the hand shape was correct. Any disagreements between raters' scores were resolved through conference and additional frame-by-frame inspection of the video data. Mean accuracy scores were computed for each patient's pantomimes to the 24 stimuli with each hand. Data for both subjects were separately analyzed using repeated measures analysis of variance (ANOVA) with stimuli as the random factor and hand as the fixed factor.

Experiment 2

Procedure

Patients were presented with tools in three formats: (1) as single-word tool names presented verbally by the experimenter, (2) as the actual 3-D objects presented on a table in front of the subjects, (3) as line drawings presented center field on a computer screen until responses were completed. These pictures subtended approximately $2^\circ \times 2^\circ$ of visual angle when viewed from 57 cm. Patients were instructed to pantomime the tool-use action associated with each of the 24 objects for all three formats using the left and right hands. In the presence of the actual tools, pantomimes were produced without contacting the objects. Each patient completed one set with each hand for each type of stimulus, beginning with their dominant hands. Responses were videotaped and coded as described above for Experiment 1.

Experiment 3

Procedure

Line drawings of tools were displayed for 200 msec to the left or right of a central fixation point. Pictures subtended a visual angle of approximately $2^\circ \times 2^\circ$ and their innermost edge was 2.0–3.0° of visual angle from fixation when viewed from 57 cm. Subjects were instructed to maintain fixation throughout the experiment. Fixation was monitored by the experimenter, and stimuli were manually triggered only after fixation was achieved. As in the previous experiment, patients were instructed to pantomime the action associated with each tool as accurately as possible. The visual field in which the objects appeared varied pseudorandomly, subject to the constraint that no more than three trials in a row could involve the same visual field. Subjects completed 8 blocks, 4 with each response hand. In each block, the 24 stimuli appeared twice, once in each visual field. Order of the blocks was counterbalanced. Video-recorded pantomimes were scored as described above in Experiment 1. Similarly, data for each subject were again separately analyzed using repeated measures ANOVA with stimuli as the random factor.

Experiment 4

Procedure

Patients were presented with a series of movie clips in the center of a computer screen. Each 10-sec clip depicted the experimenter pantomiming the use of one of the 24 tools twice and was followed by the appearance of a fixation point in the center of the screen. Clips subtended approximately $4^\circ \times 6^\circ$ of visual angle when viewed from 57 cm. After 750 msec, two pictures of tools appeared in the upper and lower quadrants of either the left or right visual fields for 200 msec. Pictures subtended $2^\circ \times 2^\circ$ of visual angle and the innermost edges of the stimuli were 2.0–3.0° from fixation when viewed from 57 cm. Patients were instructed to watch the movie clip, fixate the central cross-hair, and then point to the tool associated with the experimenter's pantomimed action. Fixation was monitored by the experimenter, and stimuli were manually triggered only after fixation was achieved. The visual field in which the objects appeared and the location of the correct object (upper or lower quadrant) varied pseudorandomly subject to the constraint that no more than three trials in a row could involve the stimuli in the same visual field. Pointing responses were made with the left and right hands in separate blocks and were manually recorded by the experimenter. Each subject performed 4 blocks with each hand in counterbalanced order beginning with their dominant hand.

Analysis

Each patient's accuracy data were analyzed individually using a multidimensional χ^2 test in which each hemisphere serves as a control for the other (Winer, Brown, & Micels, 1991). The factorial design of the experiments allows higher order interaction effects to be evaluated in a manner directly analogous to ANOVA. The factors were response (pointing location), position of the correct stimulus (upper or lower quadrant of the computer screen), hand of response (right or left), and visual field (right or left).

APPENDIX

Identity of the 24 Stimulus Items Used in All Three Experiments Drawn from Snodgrass and Vanderwart (1980)

1	Toothbrush	13	Knife
2	Pliers	14	Wineglass
3	Cigarette	15	Comb
4	Pipe	16	Glass
5	Screw	17	Plug
6	Hammer	18	Pen
7	Wrench	19	Key
8	Pencil	20	Nut
9	Cup	21	Saw
10	Screwdriver	22	Fork
11	Scissors	23	Spoon
12	Pitcher	24	Brush

Depending on the conditions detailed earlier, these items could be presented as verbal names, the actual objects themselves, or line drawings.

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