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Motor knowledge is one dimension for concept organization: Further evidence from a Chinese semantic dementia case

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ABSTRACT

Neuropsychological and neuroimaging studies have indicated that motor knowledge is one potential dimension along which concepts are organized. Here we present further direct evidence for the effects of motor knowledge in accounting for categorical patterns across object domains (living vs. nonliving) and grammatical domains (nouns vs. verbs), as well as the integrity of other modality-specific knowledge (e.g., visual). We present a Chinese case, XRK, who suffered from semantic dementia with left temporal lobe atrophy. In naming and comprehension tasks, he performed better at nonliving items than at living items, and better at verbs than at nouns. Critically, multiple regression method revealed that these two categorical effects could be both accounted for by the charade rating, a continuous measurement of the significance of motor knowledge for a concept or a semantic feature. Furthermore, charade rating also predicted his performances on the generation frequency of semantic features of various modalities. These findings consolidate the significance of motor knowledge in conceptual organization and further highlights the interactions between different types of semantic knowledge.

1. Introduction

One type of critical findings that advanced our understanding of the semantic system is that brain-damage may impair different categories of knowledge disproportionately, such as living things vs. nonliving things (Warrington & McCarthy, 1983; Warrington & Shallice, 1984; see Capitani, Laiacona, Mahon and Caramazza (2003), for a review), or objects/nouns vs. actions/verbs (Laiacona & Caramazza, 2004; Miceli, Silveri, Nocentini, & Caramazza, 1988; see Shapiro and Caramazza (2003), for a review). One influential notion motivated by such observations assumes that semantic memory is (at least partially) distributed in subsystems corresponding to different modality-specific types of knowledge (e.g., visual, motor, tactile, function, etc., Bird, Howard, & Franklin, 2000; Cree & Mcrae, 2003; Martin, Ungerleider, & Haxby, 2000; Vigliocco, Vinson, Lewis, & Garrett, 2004; Warrington & Shallice, 1984). Furthermore, the significance of a certain knowledge type varies across different semantic/grammatical categories of concepts. Therefore, selective impairment or preservation of certain types of knowledge may lead to categorical effects.

In this article, we present evidence for the significance of one specific modality of semantic feature (knowledge) – motor knowledge – in the representation of concepts and other semantic features. The importance of motor knowledge in the representation of object concepts, especially manipulable objects, has been reported in both neuropsychological and brain imaging research. Warrington and McCarthy (1987) reported a case Y.O.T., who was significantly more impaired in the comprehension of small manipulable objects (e.g., fork, shoe) than large artifacts (e.g., ship, house), living things and foods. The authors attributed this dissociation to the difference between the weights of motor (i.e., action derived) knowledge in these classes of objects. Complimentary to this pattern, later studies reported the association between better performance on manipulable objects than non-manipulable ones and the preservation of motor knowledge (Magnie, Ferreira, Giusiano, & Poncet, 1999; Sirigu, Duhamel, & Poncet, 1991). In a group study, Buxbaum and Saffran (2002) showed that apraxic patients were more impaired with tools than with animals and with manipulation knowledge than with function knowledge. The non-apraxic patients exhibited the opposite pattern. These results indicated the greater significance of motor knowledge for tool concepts than for other non-manipulable objects (e.g., animals and large artifacts).

The association between tool concepts and motor knowledge is further observed on the anatomical level. Patients showing tool-specific impairment tended to have lesions encompassing brain regions associated with motor and visual-motion processing, such as the left fronto-parietal and posterior middle temporal regions

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(Gainotti, 2000; Tranel, Damasio, & Damasio, 1997; Tranel, Kemmerer, Adolphs, Damasio, & Damasio, 2003). Similarly, functional brain imaging studies showed that processing tool items tended to induce greater activations in these regions relative to other objects (e.g., animals) (Chao, Haxby, & Martin, 1999; Martin, Wiggs, Ungerleider, & Haxby, 1996).

The significance of motor knowledge has also been assumed for the conceptual representation of actions (verbs) (Warrington & McCarthy, 1987). Both lesion studies and functional brain imaging studies have reported that brain regions associated with action/verb processing included the left fronto-parietal and posterior middle temporal regions (Gainotti, Silveri, Daniele, & Giustolisi, 1995; Martin, Haxby, Lalonde, Wiggs, & Ungerleider, 1995; Perani et al., 1999; Tettamanti et al., 2005; Tranel et al., 2003), similar to the brain regions involved in tool processing as described above. Indeed, some authors have proposed that the noun/verb differences might be reduced to the weighting differences of motoric knowledge (Arévalo et al., 2007; Saccuman et al., 2006), or of distribution differences of various feature types including motoric ones (Vigliocco et al., 2004; Vigliocco et al., 2006; but see Bedny, Caramazza, Grossman, Pascual-Leone and Saxe (2008)). For instance, in an fMRI study Saccuman and colleagues (2006) manipulated the grammatical categories (nouns or verbs) and the motoric characteristics (involves hand or not), and found significant effects of motoric fashion but no effect of grammatical class.

The importance of motor knowledge for objects were quantified by Magnie and colleagues (2003) using a manipulability index. They asked healthy subjects to rate how easily an object could evoke actions that unambiguously allow its recognition (labeled "charade rating" here).[2] Indeed, they found that artifacts and living things differed systematically on the charade rating. The charade rating was used to account for semantic category-specific object naming performance of a case (AD; Wolk, Coslett, & Glosser, 2005). AD showed significant advantage in naming nonliving things than naming living things. However, the patient's naming performance was also a function of Magnie's charade rating for the item set, leading the authors to conclude that the categorical effect could be reduced to a motor-knowledge effect. Interestingly, although AD's performances on naming objects (nouns) did not differ significantly from naming actions (verbs), he named human actions, for which charade ratings are presumably high, significantly more accurately than non-human actions (26/29 vs. 11/19). This trend implied the potential role of charade rating in predicting some patients' performance for both nouns and verbs. Nevertheless, the charade ratings for actions were not available, leaving it open whether the charade effect functions across nouns and verbs similarly.

The role of charade rating in the relationship between motor knowledge and other modalities of knowledge has also been implicated in a recent fMRI study (Mahon et al., 2007). The authors contrasted stimulus-specific repetition suppression (RS) effects for animals and three types of artifacts that differed by charade ratings: tools, arbitrarily manipulable objects, and non-manipulable ones. They observed that viewing tool pictures, whose charade ratings were the highest, elicited the strongest RS effect in the ventral visual-form processing regions (medial fusiform gyrus), along with dorsal regions processing motor and motion information (left inferior parietal lobule and left middle temporal gyrus). Functional connectivity was also found between areas showing RS for tools on the ventral and the dorsal streams. While such results can be explained by tool-specific processing circuits, as suggested by the authors, they may also reflect the potential modulation of motor knowledge, measured by charade rating, on the visual-form modality.

To summarize briefly, previous reports using various approaches demonstrated the effect of motor knowledge weightings in explaining the object recognition or naming performance patterns. It remains open whether the motor knowledge significance (charade rating) predicts performances of actions (verbs) in the same manner, or even those of modality-specific semantic features, as suggested by the results in Mahon et al. (2007). These two issues are of central interest here. In this article, we reported a Chinese patient suffering from left temporal lobe atrophy, who showed disproportionate semantic impairments for nouns (objects) relative to verbs (actions) and for living things relative to nonliving things within nouns. To anticipate, both his semantic- and grammatical-category-specific deficits could be interpreted by a continuous effect of charade ratings. Furthermore, such charade rating played a similar role in predicting his performances with semantic features of various modalities.

2. Case background

XRK is a 68-year-old, right-handed Chinese man with a college education. He worked as a college professor and then a restaurant manager. He came to the neurological clinic in 2007, showing anomic and emotional symptoms, and reported that since 2005 he had started to notice deterioration in naming familiar people, followed by fruits, vegetables, and then animals. An MRI performed in March 2007 revealed remarkable atrophy in both the lateral and medial aspects of the whole left temporal lobe, with narrowed gyri and widened sulci in the left inferior, middle, and superior temporal regions, including fusiform gyrus and hippocampus (see Fig. 1, panels A and B). A SPECT (see Fig. 1, panel C) and a MRA performed at the same time did not reveal any visible abnormalities. No symptoms of amnesia or spatial disorientation were observed by XRK or his family. His performances on various clinical neuropsychological evaluations, including MMSE (Folstein, Folstein, & McHugh, 1975), WMS-RC (Gong, 1989), Rey–Osterrieth complex figure test (ROCF; Guo, Lv, & Hong, 2000) and the Performance Subsets of WAIS-RC (Gong, 1982) were all within the normal range. However, he showed impairment on the Verbal Subsets of WAIS-RC (XRK: 81; cut-off: >84), along with various language and semantic tests. He was clinically diagnosed as semantic dementia (SD).

A set of language assessments conducted in 2007 revealed several aspects of XRK's language and/or semantic deficits. He performed poorly on two sets of naming tests: Huashan naming test (HNT; developed by Guo; including pictures of common objects of various living and nonliving categories): 32/100 correct; naming test in Aphasia Battery of Chinese (ABC; Gao & Benson, 1990): 13/20. He made frequent semantic errors (e.g., "lemon" → "banana"; "saw" → "scissors"; "teapot" → "teacup"; "injector" → "liquid medicine"). He was severely impaired in category fluency (XRK: 10 for animals, fruits, and vegetables; normal range: >30). He also had reading difficulty (62/100) and showed surface dyslexic symptoms by erroneously reading the phonetic radical of target characters (e.g., "空", /kong1/[3] for 腔, /qiang1/; "分", /fen1/ for 盼, /pan4/) (Bi, Han, Shu, & Weekes, 2007; Yin & Butterworth, 1992). He was perfect in word and sentence repetition, however (20/20). He was also impaired in a set of comprehension tests (see Section 3.1 and Table 1). His spontaneous speech was fluent and grammatically acceptable with word finding difficulties, as demonstrated by his description of the Cookie Theft Picture:

[2] Note that different from other definitions of manipulability index (e.g., "objects that can/cannot be manipulated and actions which do/do not involve fine hand movements", Arévalo et al., 2007), this charade rating does not confine to hand motors.

[3] We used the pinyin system for the phonetic transcript of the Chinese characters. The number represents the tone of the preceding syllable.

"一个母亲在洗东西，结果嘛，这个水嘛掉下来了，出事情了，她一面在洗一面在讲，两个孩子爬上去了要拿一个吃的，拿吃的东西，哦，儿子拿了嘛，给女儿， 结果拿到一半嘛， 这个 座位就掉下来了， 就要倒地了。所以，就连着几档危险的事情在吃饭的时候，就 大概就这些事情了。" (a mother was washing things. As a result, the water fell down. So something went wrong. She was speaking while washing. Two children were climbing up to get an eating thing, to get an eating. The son got it and gave it to the daughter. But the seat fell down while he was doing that. He was going to fall down to the ground. So, several dangerous things happened during a meal. That's all).

In contrast to XRK's language impairment, he displayed well-preserved knowledge of object use. We gave him a set of tools ($N = 11$) and asked him to demonstrate how to use it. His responses were videotaped to be rated by four naive judges about how well the gesture was for the target object on a 5-point scale (1 = completely wrong; 2 = partially wrong; 3 = I do not know; 4 = essentially correct; 5 = perfect). For eight objects his responses were rated as appropriate ($\geqslant 4$) by all raters, and for the other three objects three of the four raters rated as appropriate.

Interesting patterns emerged in these initial assessments included two types of categorical effects in naming: (1) XRK named actions better than objects in the naming test in ABC (5/5 vs. 8/15: $\chi^2 = 3.6$, $p = .06$) and (2) artifacts better than living things in HNT (24/60 vs. 8/40: $\chi^2 = 4.4$, $p < .05$). Relating to his normal performance in object use, our target question is whether his preservation of motor knowledge could interpret his behavioral patterns. To anticipate, we first established the two types of dissociations by using a larger item samples, then examined the underlying causes and subsequent implications by carrying out multiple regression analyses and further feature generation tests.

3. Experimental study

3.1. Contrasting different categories: living vs. nonliving; noun vs. verb

To fully assess XRK's knowledge about items across these categories, we administered groups of tests tapping into different processing stages: visual recognition; verbal comprehension; nonverbal comprehension, and single word production. For all tests, there was no time constraint to respond, and XRK's first complete responses were scored. Most tests were also given to a group of control subjects that were matched to XRK on education or age level. To examine the potential differences of XRK's performance across categories, we used χ^2-test and a program developed by Crawford and Garthwaite (2005) (C&G-test) which takes into account the distributions of normal controls. All tests were carried out in 2007 if not otherwise noted.

3.1.1. Investigation of the living–nonliving dissociation

3.1.1.1. Methods. The following tests contrasting processing of living and nonliving things were conducted.

3.1.1.1.1. Snodgrass picture naming ($N = 232$). Line drawings from the Chinese version of the Snodgrass and Vanderwart (1980) item set (Shu, Cheng, & Zhang, 1989) were presented to XRK for oral naming.

3.1.1.1.2. Mahon picture naming ($N = 80$). This picture set contains black–white photographs of 20 animals and 60 inanimate objects, which vary by degrees of charade ratings: tools, arbitrarily manipulated objects, non-manipulable objects (Mahon et al., 2007).

3.1.1.1.3. Object decision ($N = 90$). In this test, the subjects need to judge whether a target picture is a real object or not. We used items from the object decision task in Caramazza and Shelton (1998), discarding those that were too difficult for Chinese subjects (controls' accuracy <80%).

3.1.1.1.4. Attribute judgement ($N = 322$). In this task, participants needed to judge whether a statement about an object was true or false (e.g., "a rooster has a short curly tail") (adapted from Caramazza and Shelton (1998)).

3.1.1.2. Results. XRK and controls' accuracy are shown in Table 1, along with results of the statistical comparison results between living and nonliving categories. In the Snodgrass picture naming, object decision and attribute judgement, XRK exhibited better performance on nonliving than living items. On the Mahon's picture set, the living–nonliving difference was not significant, but a charade-rating effect was observed: high charade items (tools and arbitrarily manipulated objects) were named more accurately than low charade ones (non-manipulable objects and animals) (15/40 vs. 6/40, $\chi^2 = 5.23$, $p < .05$). A further note is that for objects that he failed to name, he quite often described how to manipulate them or the movements associated with them (e.g., "snail" → "I cannot name it, it crawls slowly"; "swing" → "A thing that swings back and forth").

3.1.2. Investigation of the noun–verb dissociation

3.1.2.1. Methods. We administered the following tasks comparing performances with nouns (objects) and verbs (actions).

3.1.2.1.1. Object/action picture naming I ($N = 82$). Line drawings of common objects and actions were used, where noun targets and verb targets were matched on a variety of psycholinguistic variables such as frequency, word length, age-of-acquisition, and morphological structures.

3.1.2.1.2. Object/action picture naming II ($N = 117$). Adopting items from (Arévalo et al., 2007), 58 object pictures and 59 action pictures were used. The items were further divided into hand-related items ($N = 63$) and non-hand-related items ($N = 54$).

3.1.2.1.3. Picture–word verification ($N = 210$). In this task, the subjects heard a word along with a picture, and were asked whether they matched each other (Bi, Han, Shu, & Caramazza, 2007).

3.1.2.1.4. Picture associative matching ($N = 104$). The Chinese adaptation of the pyramids and palm trees test (PPT; Howard & Patterson, 1992) and the kissing and dancing test (KDT; Bak & Hodges, 2003) were administered to assess the semantic knowledge of nouns (objects) and verbs (actions). In each trial of both tests, a target picture was presented along with two pictures, and the task was to select the one that is more related to the target. This test was done in early 2009.

3.1.2.1.5. Word associative matching ($N = 104$). The tests were identical to the picture associative matching tests, except that words were used instead of pictures. This test was done in early 2009.

3.1.2.2. Results. Across all tests but picture associative matching XRK showed better performances with verbs (actions) than with nouns (objects). For picture associative matching, his performance for both nouns (PPT) and verbs (KDT) were close to the chance level (31/52 vs. 26/52, 32/52 vs. 26/52, $ps > .23$) and therefore may shadow any potential noun–verb differences. In the object/action naming II, XRK's performances on hand-related trials and non-hand-related trials were comparable (27/63 vs. 20/54, $\chi^2 < 1$). Similarly to our observation in Session 3.1.1, he again often described the actions or movements associated with the target objects and actions (e.g., "kite" → "to play with, flies in the sky, made of paper, people pull it"; "yoyo" → "to play, roll the string around, put on hand, put it down and pull up"; "brushing teeth" → "to wipe, wipe something, wipe teeth"; "drip" → "fall, water falls down").

3.2. Explaining the categorical dissociations with the charade effect

In this session, we attempt to evaluate whether an object or action's charade rating, i.e., the predictability of target concept from

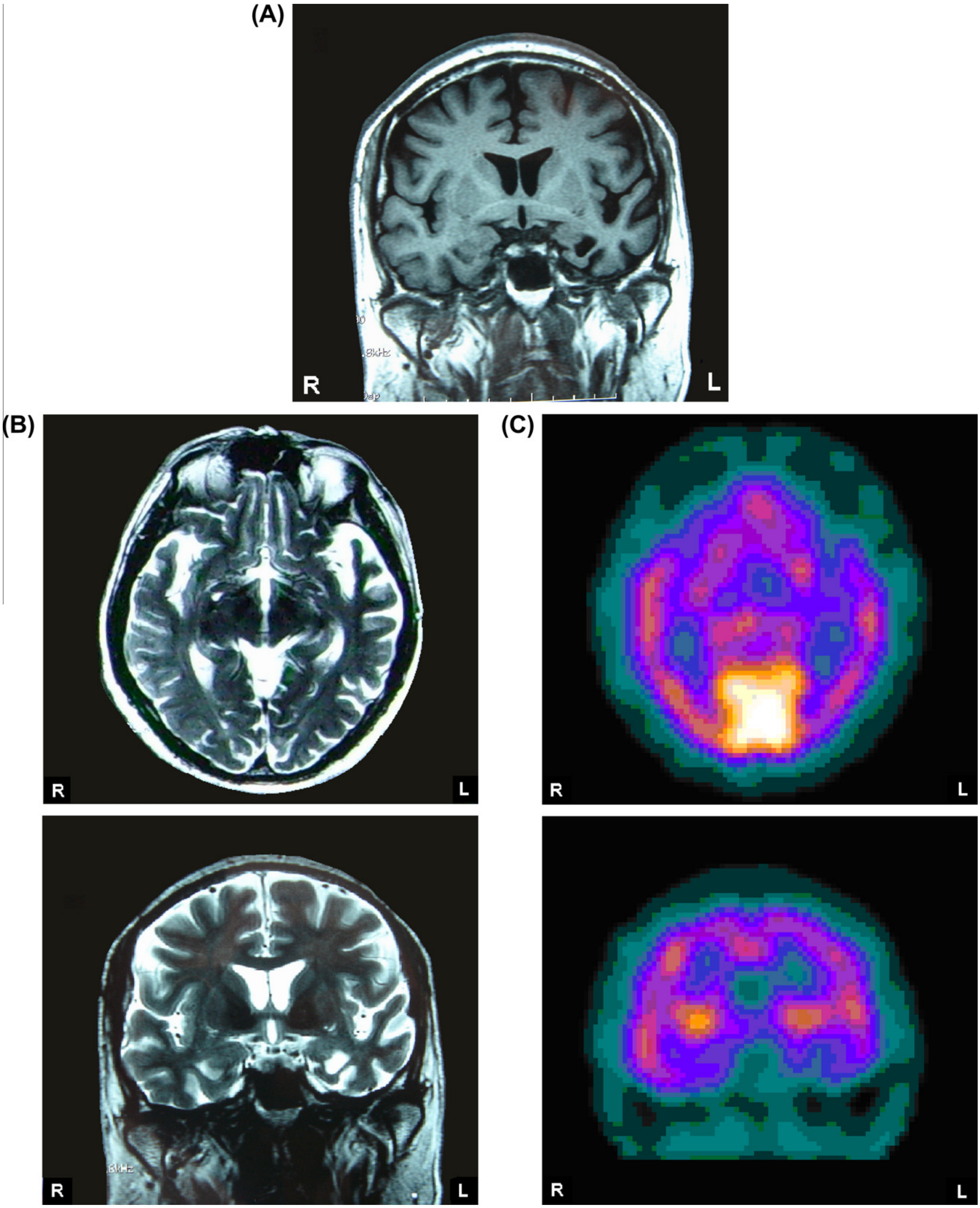

Fig. 1. (A) A T1-weighted fluid attenuated inversion recovery (FLAIR) MRI image of XRK. (B) T2-weighted fast-spin echo (FSE) MRI images of XRK. (C) SPECT images of XRK.

relevant action, can explain XRK's dissociations in object and action naming. One motivation to do this analysis is the observation that he tended to describe the related manipulations and motions in picture-naming tests as described above. Furthermore, XRK's atrophy was most apparent in the left temporal regions, leaving parietal and frontal regions relatively intact. Given that motor-related knowledge is assumed to be processed by the parietal and frontal regions (Gainotti et al., 1995; Pulvermüller, 2005; Tranel et al., 2003), the potential motor-knowledge advantage might be able to explain the categorical dissociations we observed earlier. Note that we did not carry out similar analyses on the non-naming tasks because in those tasks usually multiple items are involved (e.g., picture associative matching) and it is difficult to estimate the effective index for the motor knowledge relevance.

Table 1
Tests of XRK's living–nonliving and noun–verb dissociations.

Tests	XRK			Controls			p value (C&G)
	Percentage (correct/all)		p value (χ^2)	Mean percentage (SD)		N	
Living–nonliving dissociation							
	Living	Nonliving		Living	Nonliving		
Snodgrass picture naming	18% (13/73)	45% (71/159)	<.001	96% (3.0%)	97% (3.1%)	9	<.001
Mahon picture naming	20% (4/20)	28% (17/60)	n.s.	–	–	–	–
Object decision	79% (41/52)	92% (35/38)	0.09	95% (3.9%)	94% (4.5%)	15	<.05
Attribute judgement	79% (130/164)	89% (140/158)	<.05	95% (2.9%)	95% (2.5%)	15	<.01
Noun–verb dissociation							
	Noun	Verb		Noun	Verb		
Object/action picture naming I	46% (22/48)	74% (25/34)	<.05	90% (6.0%)	91% (5.6%)	16	<.01
Object/action picture naming II	25% (15/59)	55% (32/58)	<.01	–	–	–	–
Picture–word verification	74% (119/162)	85% (41/48)	0.09	95% (3.0%)	93% (3.2%)	14	<.05
Picture associative matching	60% (31/52)	62% (32/52)	n.s.	81% (5.0%)	83% (8.9%)	6	n.s.
Word associative matching	54% (28/52)	83% (43/52)	<.01	–	–	–	–

Note: "*P* value (C&G)": statistical results derived from the program developed by Crawford and Garthwaite (2005); "n.s.": no significance; "–": not be tested.

3.2.1. Charade effect and living–nonliving dissociation

To elucidate whether XRK's living/nonliving dissociation in object naming could be accounted for by the charade effect, we carried out a binary logistic regression analysis on his performance on the Snodgrass picture-naming test. The dependent variable was XRK's score for each item ("1" for correct, "0' for incorrect). Two critical predictors were the charade rating (Magnie et al., 2003) and semantic domain (living/nonliving), as we were most interested in whether the charade rating can fully explain the effect of semantic domain on XRK's performances. We further included several predictors to partial out potentially confounding variables (see Funnell and Sheridan (1992), Magnie et al. (2003) and Stewart, Parkin and Hunkin (1992)): word frequency (Sun, Huang, Sun, Li, & Xing, 1997), familiarity and visual complexity (Shu et al., 1989). No pair-wise correlation of predictors was higher than .70, ruling out the potential multicollinearity problems following the rule generally adopted for regression studies (Baayen, Feldman, & Schreuder, 2006).

We developed the following two types of regression models. In the first set of regression models, we included the nuisance predictors and the "semantic domain" predictor, but not the charade-rating predictor. In the second model set, we additionally included the charade-rating predictor. The critical question is whether any significant effect of semantic domain in the first model set would still survive after the inclusion of charade rating in the second model set. Specifically, in both sets of models, we used two types of entering methods to consolidate the unique contributions of each predictor: simultaneous entering and two-step hierarchical methods. In the simultaneous entering method, all predictors were simultaneously introduced into regression model. In the two-step hierarchical method, separate models were developed for each predictor (e.g., semantic domain), such that all other predictors (word frequency, familiarity, visual complexity, etc.) were entered in the first step, and then the predictor of interest (semantic domain) entered in the second step. In this way, the unique contribution of the predictor in the second step was illustrated. The results from these regression methods are shown in Table 2. As can be seen under the "regression without charade rating" heading, besides word frequency and familiarity, semantic domain had significantly predictive power in XRK's naming performance, using both the simultaneous entering method and the hierarchical method. Critically, when charade rating was included as a predictor, semantic domain no longer had significant effect. The naming performance was significantly predicted by charade rating, word frequency and familiarity.

To examine whether the charade effect was mainly driven by items in one particular domain, we further carried out analyses within the two semantic domains (living and nonliving) separately. Charade effect was significant within the living domain (*ps* < .005 for both entering methods) and was marginally significant for the nonliving items (*ps* < .1 for both entering methods), indicating that charade rating was a significant predictor of naming performance for all items.

3.2.2. Charade effect and noun–verb dissociation

We used the logistic regression methods identical to the ones used in Section 3.2.1 here to examine the effects of grammatical class (noun/verb) and charade rating in XRK's picture naming performance. To maximize the item number, we included all 511 items from the four picture naming tasks (Snodgrass picture naming; Mahon picture naming; Object/action picture naming II & I). The dependent variable was still XRK's score for each item ("1" for correct, "0" for incorrect). The predictors for this session were charade rating, grammatical class, word frequency (Sun et al., 1997), and familiarity. Visual complexity was not included in this session because the rating was not available for many items and that it did not yield any effect in the regression analyses above.

Because the charade rating in the literature (Magnie et al., 2003; Mahon et al., 2007) were exclusively for nouns, we collected our own ratings for the nouns and verbs in the current analyses. We presented target words and adopted the instructions from Mahon et al. (2007), which were applicable for both nouns and verbs: "Suppose you were playing charades, such that one person had to identify a word based on how another person mimed various actions that might be associated with its meaning. You are asked to rate, for the following words, how difficult it would be to play that game with these items (1 = very difficult/impossible; 7 = very easy)". Sixteen naive undergraduate subjects were asked conduct the rating on a 7-point scale. Another sixteen subjects participated in the familiarity rating for the whole item set, presented with target words and instructions adopted from Shu et al. (1989). Our rating results were well correlated with those of previous studies (Charade rating: $R_{\text{current-Magnie}} = .60$, $R_{\text{current-Mahon}} = .71$; familiarity rating: $R_{\text{current-Shu}} = .67$).

The regression results are displayed in Table 2. No pair-wise correlation of predictors was higher than .70. The regression results without the charade rating as a predictor showed that grammatical class, in addition to word frequency and familiarity, significantly predicted XRK's naming performance. Critically, the second analysis showed that once charade rating was included in the regression model, it replaced grammatical class as a significant predictor for XRK's performance.

We also carried out logistic regression analysis for nouns and verbs separately, using word frequency, familiarity, and charade

Table 2
Results of the binary logistic regression analyses.

	Simultaneous entering method				Two-step hierarchical method	
	B	S.E.	Wald	Sig.	Change of −2 log likelihood	Sig.
Charade effect and XRK's living–nonliving dissociation						
Regression without charade rating						
Semantic domain	1.00	0.43	5.33	<.05	5.65	<.05
Word frequency	1.01	0.25	15.85	<0.001	17.46	<0.001
Familiarity	1.18	0.27	18.70	<0.001	21.85	<0.001
Visual complexity	0.21	0.21	0.99	n.s.	1.00	n.s.
Regression with charade rating						
Charade rating	0.48	0.19	6.26	<.05	6.55	<.05
Semantic domain	0.33	0.51	0.42	n.s.	0.42	n.s.
Word frequency	1.06	0.26	16.61	<0.001	18.50	<0.001
Familiarity	1.11	0.27	16.23	<0.001	18.69	<0.001
Visual complexity	0.21	0.22	0.92	n.s.	0.93	n.s.
Charade effect and XRK's noun–verb dissociation						
Regression without charade rating						
Grammatical class	1.00	0.27	13.50	<0.001	13.83	<0.001
Word frequency	0.76	0.17	20.06	<0.001	20.98	<0.001
Familiarity	0.70	0.11	42.50	<0.001	51.23	<0.001
Regression with charade rating						
Charade rating	0.39	0.10	15.71	<0.001	16.15	<0.001
Grammatical class	0.44	0.31	1.96	n.s.	1.96	n.s.
Word frequency	0.73	0.17	18.05	<0.001	18.80	<0.001
Familiarity	0.56	0.11	23.78	<0.001	26.23	<0.001

rating as predictors. Charade rating was a significant predictor for XRK's naming performance of both nouns and verbs: nouns: $ps < .001$ using both simultaneous and hierarchical entering methods; verbs: $ps < .05$ using both simultaneous and hierarchical entering methods.

3.3. Charade effect on the level of semantic feature

In the above sessions, we demonstrated that charades rating could predict our patient's performance on particular target objects or actions. We speculated that this is because his motor knowledge was relatively preserved. How well he could derive the target based on such preserved motor knowledge would then correlate exactly with the target's charade rating.

An open question is whether the same effect applies to the semantic feature level. That is, how might the preserved motor knowledge affect the access of other types of semantic features (e.g., visual features)? It is widely assumed that semantic features correlate with each other in complex manners (Caramazza, Hillis, Rapp, & Romani, 1990; Tyler, Moss, Durrant-Peatfield, & Levy, 2000; Vigliocco et al., 2004). Then it is possible that the non-motor features are affected by the motor-knowledge advantage to different degrees. Those features (e.g., "having four legs") that can be more strongly predicted by the motor knowledge (walking, running, jumping, etc.) would benefit more from the preserved motor knowledge than other features (e.g., "being red").

To examine the validity of this hypothesis, we carried out a feature generation task and analyzed the characteristics of the features produced by XRK. We gave the 80 target words from Mahon et al. (2007) and asked XRK to provide any many features as possible without time constraint. Among the 80 items, 55 were included in the feature generation norm developed by Cree and McRae (2003) and were analyzed here. In Cree and McRae (2003), healthy subjects were asked to generate features, and for each word, the features that were produced by at least five of 30 participants were considered in the feature norm. For the 55 target concepts, the norm listed 800 semantic features in total. We collected charade ratings on these 800 features with 12 undergraduate/graduate students. We presented each semantic feature in a statement beginning with a pronoun "it" (e.g., it is heavy) and used the following instruction "Suppose you are playing pantomime and trying to act out the following statements accurately and succinctly. You are asked to rate, for each statement, how difficult it would be to act (1 = very difficult; 5 = very easy)."

We classified the features into those with high charade ratings ($\geqslant 3$, $N = 347$) and those with low charade ratings (<3, $N = 453$). In the norm, the mean production frequency of high charade and low charade features were comparable (129/347 vs. 153/453, $\chi^2 < 1$). XRK correctly produced significantly more high charade features than low charade features (88/347 vs. 69/453, $\chi^2 = 12.8$, $p < .001$), and the difference between the high and low charade features was greater than that in the feature norm ($\chi^2 = 4.3$, $p < .05$).

To directly address the effect of motor knowledge on other types of features, we selected a subset of non-motor features ($N = 247$), including the "external component" (e.g., having four legs, having hair) and "external surface property" (e.g., being brown, being large), following the classification "WB feature types" in Cree and McRae (2003). In the norm, the mean production frequency for high charade and low charade features were comparable for these features (65/174 vs. 25/73, $\chi^2 < 1$). Again XRK produced more high charade ones than low charade ones (47/174 vs. 6/73, $\chi^2 = 1.8$, $p < .005$), and the difference between these two charade types was greater than that in the norm ($\chi^2 = 5.3$, $p < .05$).

4. Discussion

The case we presented here showed two categorical effects in naming and comprehension: better performance with nonliving items than with living items, and better performance with verbs than with nouns. Using various types of regression analyses, we observed that the items' charade ratings, i.e., the predictability of target concept from relevant action, significantly predicted his performances on both objects and actions, and could account for the categorical differences. Furthermore, charade ratings also predicted his performances on the production of semantic features of various modalities.

Our results consolidate the significance of motor knowledge in concept representation, and are consistent with previous observations of the correlation between motor knowledge (measured by object use ability) and conceptual tasks in semantic dementia cases (Bozeat, Lambon-Ralph, Patterson, & Hodges, 2002; Hodges, Bozeat, Lambon-Ralph, Patterson, & Spatt, 2000). Our results indicated that this correlation might (at least partly) be due to the predictability of motor knowledge for conceptual tasks, as opposed to what was proposed by the authors, who argued that the object use ability was determined by the general conceptual knowledge. Note that the current results do not speak to whether motor knowledge is necessary for some concepts such as tools. Indeed, ample neuropsychological evidence has shown that object recognition and naming can be achieved without corresponding motor knowledge (for a review see Mahon and Caramazza (2007)). Rather, we believe that motor knowledge (or any modality) supports the retrieval of the corresponding concepts, other types of knowledge, and the object/action name retrieval.

Our results are in line with a wide range of theories assuming modality-specific organization of conceptual knowledge (Allport, 1985; Bird, Lambon-Ralph, Patterson, and Hodges, 2000; Cree & McRae, 2003; Mahon & Caramazza, 2009; Martin et al., 2000; Vigliocco et al., 2004), despite the variations among them in terms of the modalities being incorporated and the distribution pattern of modality-specific knowledge across categories. Furthermore, such theories about the representation of object concepts have been extended to the domain of actions (Bird, Howard et al., 2000; Vigliocco et al., 2004), assuming the same organization principal for objects and action concepts. The previously reported evidence for this school of modality-specific representation theories mainly come from observed associations between performances on motor knowledge and on categories for which motor knowledge are assumed important. Here by showing the significance predictability power of charade rating on the patient's performance, we provide the empirical evidence for the significance of motor knowledge in accessing concepts of various semantic categories (living things, nonliving things, and actions). Furthermore, our finding of the predictability effect of motor knowledge on the patient's performance on other types of (e.g., visual) knowledge is also in accord with semantic theories incorporating the interaction of features (Caramazza et al., 1990; Thompson-Schill, Kan, & Oliver, 2006; Tyler et al., 2000; Vigliocco et al., 2004). Our results presented evidence for a specific implementation of featural modulation.

While we have shown that the categorical differences in our patient can be explained by charade effect, we would not generalize such findings to all observed categorical patterns. Categorical dissociation in some cases is not likely to be reduced to the effect of one semantic-feature dimension, such as the double-dissociation patterns observed within one patient across different modalities of processing (e.g., Rapp & Caramazza, 2002). However, our results do suggest further scrutiny of some observations that were assumed to support or challenge modality-specific theories. For instance, some modality-specific theories assumed a general loss of sensory (mainly visual) knowledge to explain the specific living item impairment (e.g., Warrington & Shallice, 1984). This assumption was then investigated using direct assessment of sensory and non-sensory knowledge of individuals with or without category-specific deficits for living things (e.g., Basso, Capitani, & Laiacona, 1988; Lambon-Ralph, Patterson, Garrard, & Hodges, 2003; for a review see Caramazza and Shelton (1998)). Our results on the modulation effect between motor knowledge and visual knowledge, however, demonstrated that the direct assessment of visual knowledge might be contaminated by the effect of other modalities. In fact, it has been explicitly proposed that predictability of visual features from non-visual ones might be stronger for nonliving entities relative to living entities (Thompson-Schill et al., 2006). Further investigations of cross-modal interaction patterns for various categories are therefore warranted.

A final note is that an anatomical signature of semantic dementia is the atrophy in the anterior temporal regions with the brain areas for motor processing less affected. Consistent with this anatomical pattern, our patient showed relatively preserved motor knowledge, advantage of processing actions over objects, and nonliving things over living things. However, mixed results have been widely reported in terms of SD's behavioral patterns. Both direction of object-action dissociations have been reported (for "noun < verb" results see: Bak & Hodges, 2003; Bird et al., 2000; Breedin, Saffran, & Coslett, 1994; Daniele, Silveri, Giustolisi, & Gainotti, 1993; Papagno, Capasso, & Miceli, 2009; Silveri & Ciccarelli, 2007; Silveri, Perri, & Cappa, 2003; for "noun > verb" results see: Reilly, Cross, Troiani, & Grossman, 2007; Rhee, Antiquena, & Grossman, 2001; Yi, Moore, & Grossman, 2007), so have both directions of living–nonliving dissociations (for "living < nonliving" cases see: Barbarotto, Capitani, Spinnler, & Trivelli, 1995; Cardebat, Demonet, Celsis, & Puel, 1996; Lambon-Ralph et al., 2003; Papagno et al., 2009; Zannino et al., 2006; for "living > nonliving" cases see: Lambon-Ralph, Howard, Nightingale, & Ellis, 1998; Silveri et al., 1997). Although the effects of nuisance variables might explain some of these dissociation patterns, they seems insufficient to explain the contradictory observation within SD groups. For example, Bird, Howard et al. (2000) and Bird, Lambon-Ralph et al. (2000) attributed their "noun < verb" findings to the relatively lower frequency of nouns, but the such pattern remained in other studies when the frequencies were well matched (e.g. Silveri & Ciccarelli, 2007; Silveri et al., 2003). Similarly, it has been proposed that the "noun > verb" pattern might be explained by the relatively higher executive resource demands necessary for verb picture naming (D'Honincthun and Pillon, 2008), but this explanation does not applied to similar patterns using verbal stimuli (Reilly et al., 2007; Yi et al., 2007). Given that individuals with semantic dementia vary widely in terms of brain atrophy patterns, it is likely that there is fine specificity for modality- or category- specific knowledge within the temporal lobe (e.g., Bi et al., in press; Damasio, Tranel, Grabowski, Adolphs, & Damasio, 2004; Miceli et al., 2001; Simmons, Reddish, Bellgowan, & Martin, 2010), and it would be premature to generalize the pattern reported here to the whole clinical group.

To conclude, by using the charade rating as a measurement of the significance of motor knowledge for a concept or a semantic feature, we observed the effect of motor knowledge in predicting the patient's performance on semantic processing. These results consolidate the role of motor knowledge, which is represented in areas outside of the temporal regions, in the organization of the conceptual system and underscore the importance of considering cross-modal featural interactions in future studies.

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