

at the apple to pick it up, and finally at the box for placement. When the unambiguous instruction was presented in the one-referent context, participants never looked at the incorrect destination (13) (Fig. 1).

In the two-referent context, participants often looked at both apples shortly after hearing "the apple," which reflected the fact that reference could not be established on the basis of just that input. Participants looked at the incorrect referent during 42% of the unambiguous trials and during 61% of the ambiguous trials. [In contrast, in the one-referent context, in which reference could be established given just "the apple," individuals rarely looked at the incorrect object (pencil); this occurred during 0 and 6% of the trials for the ambiguous and unambiguous instructions, respectively.] The time it took participants to establish reference correctly in the two-referent context did not differ for the ambiguous and unambiguous instructions, which indicates that "on the towel" was immediately interpreted as a modifier, not as a destination. Individuals then typically looked directly to the box for object placement without looking at the incorrect destination (Fig. 2). In contrast with the one-referent context, ambiguity in the instruction did not affect the proportion of eye movements to the incorrect destination in the two-referent context (14) (Fig. 3).

Our results demonstrate that in natural contexts, people seek to establish reference with respect to their behavioral goals during the earliest moments of linguistic processing. Moreover, referentially relevant nonlinguistic information immediately affects the manner in which the linguistic input is initially structured. Given these results, approaches to language comprehension that assign a central role to encapsulated linguistic subsystems are unlikely to prove fruitful. More promising are theories by which grammatical constraints are integrated into processing systems that coordinate linguistic and nonlinguistic information as the linguistic input is processed (10, 15). Finally, our results show that with well-defined tasks, eye movements can be used to observe under natural conditions the rapid mental processes that underlie spoken language comprehension. This paradigm can be extended to explore questions on topics ranging from recognition of spoken words to conversational interactions during cooperative problem solving.

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5. We monitored eye movements with an Applied Scientific Laboratories camera that was mounted on a lightweight helmet. The camera provides an infrared image of the eye at 60 Hz. The center of the pupil and the corneal reflection are tracked to determine the orbit of the eye relative to the head. Accuracy is better than 1 degree of arc, with virtually unrestricted head and body movements. For details, see D. Ballard, M. Hayhoe, J. Pelz, *J. Cog. Neurosci.* **7**, 66 (1995). Instructions were spoken into a microphone connected to a Hi-8 VCR that also recorded the field of view and eye position of the participant.
6. Eight objects were on a table with a center fixation cross. Each trial began with the instruction, "Look at the cross." The eye-movement latency difference between the conditions with and without objects with similar names was reliable [ $t(7) = 3.04$ ,  $P < 0.02$ ].
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11. The 12 critical instructions were embedded among 90 filler instructions. Each trial began with the command, "Look at the cross."
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320–358] and G. Altmann and M. Steedman [*Cognition* **30**, 191 (1988)] have developed a theory of syntactic ambiguity resolution in which referential context is central.

13. This difference between ambiguous and unambiguous instructions was reliable by a planned comparison [ $t(5) = 4.11$ ,  $P < 0.01$ ].
14. The interaction between context and ambiguity for eye movements to the incorrect destination was reliable [ $F(1,5) = 8.24$ ,  $P < 0.05$ ]. Also, a three-way interaction between context, ambiguity, and type of incorrect eye movement (to object or to destination) revealed the bias toward a destination interpretation in the one-referent context and toward a modification interpretation in the two-referent context [ $F(1,5) = 18.41$ ,  $P < 0.01$ ].
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16. We thank D. Ballard and M. Hayhoe for encouraging us to use their laboratory (National Resource Laboratory for the Study of Brain and Behavior) and for advice on the manuscript, P. Lennie and R. Jacobs for helpful comments, J. Pelz for teaching us how to use the equipment, and K. Kobashi for assistance in data collection. Supported by NIH resource grant 1-P41-RR09283, NIH HD27206 (M.K.T.), an NSF graduate fellowship (M.J.S.-K.), and a Social Sciences and Humanities Research Council of Canada fellowship (J.C.S.). All participants gave informed consent.

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## TECHNICAL COMMENTS

### Origins of Fullerenes in Rocks

Naturally occurring fullerenes have been found in rock samples that were subject to singular geologic events such as lightning strokes (1), wildfires at the K-T boundary (2), and meteoritic impacts (3). These findings are expected, as fullerenes form normally under highly energetic conditions. However, P. R. Buseck *et al.* (4) reported the presence of  $C_{60}$  in a carbon-rich rock sample from Shunga, in Karelia, Russia, in which the host geologic unit was highly metamorphosed and there was no evidence of exposure to extreme conditions. If fullerenes did form naturally in such an environment, we would expect them to be widely present elsewhere, and there would be many ramifications. For example, the presence of fullerenes in the earliest times would have implications for the evolution of life (that is, as an early source of large molecules).

We studied the occurrence and distribution of fullerenes in carbon-rich rocks, including samples of shungite from the deposit in Shunga. To avoid sources of contamination by fullerenes, our samples were prepared in laboratories where there had been no previous work done on fullerenes. The outer 2- to 4-mm portion of the shungite

samples was removed, and only the core material was gently crushed and ground before mass spectrometry (MS) analysis was carried out directly on the rock powder. Laser Fourier-transform MS and thermal desorption negative ion MS methods were used. In the thermal desorption MS, the temperature was scanned up to 450°C, at which  $C_{60}$  and  $C_{70}$  are fully volatilized. One sample was purposely contaminated with 100 ppm of commercial fullerenes as a control and to check the sensitivity of the analysis. The result of this reference test indicated that we could detect fullerenes at 10 ppm, or less, without difficulty.

The three samples from the Shunga locality (5) had a variable carbon content of about 100, 90, and 10% by weight. These samples were hosted by about 2-billion-year-old metamorphosed volcanic and sedimentary rocks of the Karelian terrain, which extends northwest through Finland and into Finnmark (northern Norway). We also analyzed one carbon-rich sample from the Bidjovagge mine near Kautokeino, Finnmark, from rocks with broadly similar age, provenance, and metamorphic history as those of Shunga.

To check other geological environments, we analyzed graphite from 3.2-billion-year-old organic carbon-rich shale from a shear zone in the Princeton Mine of the Barberton district, South Africa. Graphite from the Bogala mine, Sri Lanka, was also analyzed (6), a Precambrian sample likely from an inorganic igneous carbon source and formed at temperatures as high as 700°C at 1 to 2 kbar. In contrast, the Princeton Mine sample experienced a maximum temperature of about 300°C.

None of these samples contain detectable amounts of fullerenes. On the basis of these results, we hypothesize that the fullerenes found in the Shunga sample studied by Buseck *et al.* (4) were probably formed by a localized event such as a lightning stroke. This could have happened given the high conductivity of such carbon-rich rocks. Our results and other studies (1–4) appear to show that the formation of fullerenes in nature is limited to highly energetic singular events.

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5. We thank L. P. Galdobina for providing the shunga samples and D. Eisenheimer for providing the Sri Lanka sample.

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**Response:** Finding no fullerenes in several shungite and other samples, Ebbesen *et al.* conclude that the sample we studied (1) was

formed by a localized event such as a lightning strike. We find problems with this and other of their observations and interpretations. They state that "there was no evidence of exposure to extreme conditions" for the shungite sample in our study (1). However, we did not discuss occurrence in our report—all we had to study were chips of unknown provenance—and so Ebbesen *et al.*'s conclusion and interpretation seem unsupported. Ebbesen *et al.* also assert that "These findings [origins by lightning, K-T boundary, or meteoritic impact] are expected, as fullerenes form normally under highly energetic conditions." This statement begs the question, as the four terrestrial (1–3) and two extraterrestrial occurrences (4) of natural fullerenes to date tell little about how they form "normally."

We and others (5) have looked at a wide variety of geological samples that contain no detectable fullerenes. The question is—What does this mean? Does it necessarily indicate that only "singular events" can form fullerenes in nature? Also, if fullerenes occur in shungite, then must one conclude they should also "be widely present elsewhere?" Not necessarily.

Aside from the fact that many minerals have been found exclusively in highly limited occurrences, in some cases in only single localities, these questions cannot yet be answered—there are insufficient data. However, there are other mineralogical situations from which, by analogy, one can make at least cautionary guesses.

The biopyriboles provide one example. Although the term was coined over 80 years ago by Johannsen (6), until the late 1970s the only members were the standard mineral groups of micas (biotite), pyroxenes, and amphiboles. At that time, we saw the report of several new biopyribole minerals (7). Initially just curiosities, within a few years the new biopyriboles were reported from several dozen localities worldwide. Chesterite, jimthompsonite, and their mineralogical relatives are now well known and are accepted as widespread albeit minor, rock-forming minerals.

Another example is provided by diamond. Until the 1980s, geologists and solid-state scientists were confident they knew that diamonds form solely at extreme pressures, deep within Earth or, under exceptional conditions, in ultrahigh-pressure experiments that could only be performed in a selected few laboratories. The idea of diamonds being able to form at ambient pressures seemed impossible. Yet today chemical-vapor-deposited (CVD) diamonds, formed at ambient pressures, are almost commonplace (8) in many laboratories, both research and industrial.

The implications, if any, for geological fullerenes are admittedly tenuous. Fullerenes are not prevalent, but we are uncomfortable concluding more than that. We reported that

within the shungite they only occur within veinlets. We have confirmed that occurrence in subsequent analyses of the veinlet material in the shungite. Like Ebbesen *et al.*, we wondered whether the shungite fullerenes formed through lightning strikes but, other than the fullerenes themselves, there is no evidence on how they formed.

On the basis of laboratory data, we know that optimal fullerene growth occurs in gas-phase reactions (9), and such conditions might occur during the multiple strokes of lightning (3). Indeed, lightning might explain the origin of the fullerene-bearing veinlets in the shungite, but it would be highly fortuitous if we would have inadvertently chanced on such unusual samples. There are other references to the occurrence of fullerenes in shungite (10), but details are lacking about where in the shungite the fullerenes occur or in which samples.

There is abundant evidence that the mineralogical world is wondrously complex and full of surprises. We prefer to retain an open mind about the extent of fullerene occurrences in the geological environment than to make possibly premature conclusions based on the limited data at hand.

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