Speech production and syntax comprehension deficits on Mt. Everest

Philip Lieberman, M.S., Ph.D. and
Athanassios Protopapas, B.S., M.S.
Department of Cognitive & Linguistic Sciences
Brown University

Barbara G. Kanki, M.S., Ph.D.
NASA-Ames Research Center
Moffet Field, CA

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Deficits in speech motor control and in the comprehension of syntax were observed as five members of the 1993 American Sagarmatha Expedition ascended Mt. Everest. We analyzed speech recordings and cognitive test scores of the climbers at different altitudes. The mean "voice onset time" interval that differentiates "voiced" stop consonants from their "unvoiced" counterparts (e.g., a [b] from a [p]) decreased from 24.0 ms at Base Camp to 5.4 ms at Camp Three. The time needed to comprehend simple spoken English sentences increased by 50% at higher altitudes, and was correlated with speech motor deterioration. This pattern of deficits is similar to that noted for Parkinson's disease and may reflect disruption of subcortical pathways to prefrontal cortex. Similar procedures could be used to remotely assess cognitive impairments caused by hypoxia, carbon monoxide or alcohol intoxication, or drugs, in order to monitor crew behavior in aeronautics and spaceflight operations, or to evaluate the treatment of neurodegenerative diseases such as Parkinson's disease.

Keywords: Hypoxia, Cognitive deficits, Mountaineering, Speech production measurements, Language tests

In the seventy odd years since the ascent of Everest was first attempted climbers have frequently reported motoric and cognitive deficits at extreme altitude. Impaired judgement is implicated in many of the fatalities occurring on Everest and other 8,000 m mountains (Ward, Milledge, & West, 1989; Nelson et al., 1990). Several researchers have investigated the effects of high altitude on cognitive and motor performance. Most studies have been concerned with lasting effects after exposure to high altitude; few studies have tested mountaineers at high altitudes to investigate possible transient effects. Apart from the theoretical and scientific interest in the cognitive and motoric deficits at high altitude, such research may lead to a practical, online, unobtrusive system for remote monitoring of the effects of situation-specific impairments, such as high altitude climbing or flying, in order to reduce the risks associated with these activities.

Temporary impairments in cognitive functioning found at high altitude include deterioration of the ability to learn, remember and express information verbally (Townes, Hornbein, Schoene, Sarnquist, & Grant, 1984), impaired concentration and cognitive flexibility (Regard, Oelz, Brugger, & Landis, 1989), decline of the feeling of knowing (Nelson et al., 1990), and mild impairment in either short-term memory or conceptual tasks (Regard et al., 1991). Kennedy et al. (Kennedy, Dunlap, Banderet, Smith, & Houston, 1989) reported impairments in grammatical reasoning and in pattern comparison during a slow, multi-day, simulated ascent in a hypobaric chamber. Cognitive deficits found in climbers after a high-altitude expedition include decreased memory performance (Cavaletti, Moroni, Garavaglia, & Tredici, 1987), mild impairment in concentration, verbal learning and memory, and cognitive flexibility (Regard et al., 1989; Oelz et al., 1990), and decline in visual and verbal learning and memory (Hornbein, Townes, Schoene, Sutton, & Houston, 1989). It is unclear whether any of these deficits become permanent after repeated prolonged exposure to extreme altitude, as findings from different studies have reached opposing conclusions (cf. (Clark, Heaton, & Wiens, 1983; Jason, Pajurkova, & Lee, 1989)).

A possible explanation for the reported deficits is that brain hypoxia, caused by lowered oxygen content of the inspired air, selectively impairs some brain structures. Histologic studies of the hypoxic brain have identified regions

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of "selective vulnerability" to hypoxia in the hippocampus, cerebellum, layers III, V, and VI of the neocortex, and the basal ganglia (Brierley, 1976). According to current theories of brain function, the compromised cells in the hippocampus and the cerebellum may account for some learning (memory) and motor deficits, respectively; the consequences of the affected cortical regions may be quite extensive, possibly including deteriorations of perception, planning, and evaluation of danger. However, the possible effects of basal ganglia dysfunction at high altitude have not been investigated. In order to assess these effects, we need to take into account studies that relate lesions in the basal ganglia to particular types of deficits.

Recent studies of Broca's aphasia (Baum, 1988; Baum, Blumstein, Naeser, & Palumbo, 1990) and Parkinson's disease (Grossman, Carvell, Stern, Vernon, & Hurtig, 1991; Lieberman et al., 1992) show deterioration of speech motor control, deficits in syntax comprehension, and other cognitive deficits. Such decrements may reflect the degradation of subcortical basal ganglia pathways to prefrontal cortex (Metter et al., 1989; Metter, Riege, Hanson, Phelps, & Kuhl, 1984; Lieberman, 1991; Lange et al., 1992; Cummings, 1993). It is now known that many pathways involved in motor control as well as in higher associative or cognitive functions include connections to and from the basal ganglia (Parent, 1986). These pathways may also be implicated in the motoric and cognitive deficits reported by climbers at extreme altitude. In this study we administered a battery of tests, for which we had comparative data from Parkinson's disease, to climbers at extreme altitude. We measured speech motor control, comprehension of meaning conveyed by syntax, and "frontal" cognitive functions. These tests can be administered remotely with minimal equipment.

The speech attribute that we studied, Voice Onset Timing (VOT), differentiates English "voiced stop" consonants like [b], [d], and [g] from their unvoiced counterparts [p], [t], and [k], respectively. In order to produce a [b], a speaker has to initiate "phonation" (i.e, quasi-periodic vibration of the vocal folds) soon after opening the lips (within about 20 ms) to release the pressure built in the vocal tract. In contrast, phonation is delayed for 40 ms or more after lip opening in a [p]. Similar timing distinctions differentiate [d]s from [t]s and [g]s from [k]s. Figure 1 shows the waveforms for a [b] and a [p] produced by the same speaker, where the lip opening (identified by a visible burst) and the onset of phonation (evidenced by periodicity in the waveform) have been marked. The time delay between the marks is the VOT. Normally, speakers of English and many other languages maintain the VOT distinction between voiced and unvoiced word-initial stop consonants by keeping the VOT regions of the two separated by at least 20 ms. Listeners make use of this cue to differentiate stop consonants in word-initial position (Lisker & Abramson, 1964).

Syntax comprehension was assessed by the Rhode Island Test of Language Structure (RITLS), a test initially designed

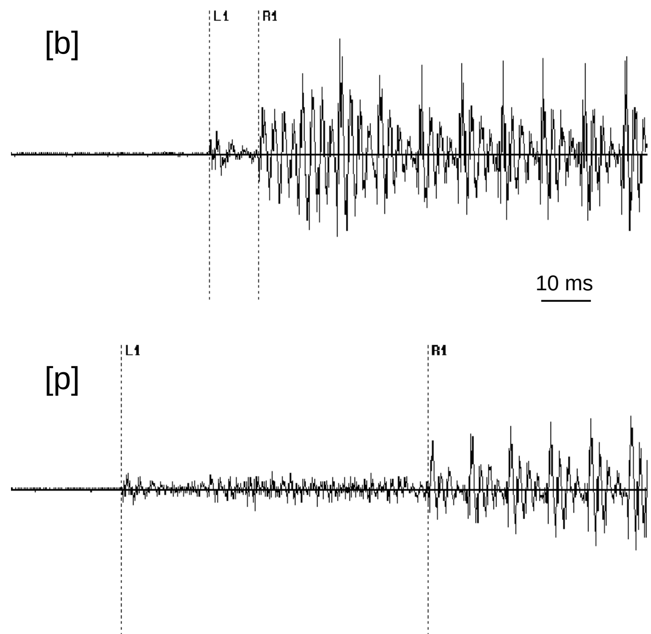

Figure 1. Speech waveform segments corresponding to a [b] and a [p] spoken by the same speaker under identical conditions. Cursors have been placed at the onset of the burst that was caused by opening the lips (L1) and at the onset of periodicity that indicates vocal fold vibration (R1). The marked interval, Voice Onset Timing (VOT) is used by speakers and listeners to differentiate the two types of consonants in word-initial positions.

to evaluate hearing impaired children. The RITLS assesses the extent to which subjects are able to use syntactic properties of sentences (word order, markers of the relationships between clauses, and markers of non-canonical order) to understand them. It includes "simple" sentences (consisting of a single clause) and "complex" sentences (containing embedded clauses), presenting a representative sample of the syntactic structures of English. Vocabulary and morphology are tightly controlled and sentence length is balanced between simple and complex sentences. The vocabulary is kept very simple and none of the sentences are very difficult; normal 10 year old native English speaking children make almost no errors on either the simple or the complex sentences (Engen & Engen, 1983). In this study we measured processing difficulty by timing the subjects' responses.

Methods

Subjects

The subjects were five male members of the 1993 American Sagarmatha Expedition team to Mount Everest. Their ages ranged from 35 to 52 years and their education from

High School to M.D. Informed consent was obtained from all members of the original team (eight males and one female); however, some members dropped out of the study for a variety of reasons. All the subjects were experienced climbers (each had at least eight years of experience on major peaks). Sherpas worked closely with the team but they did not officially participate in the study. The study procedures were approved by the Brown University Human Subjects Committee.

Materials and Locations

The expedition approached Mount Everest by the "normal" South Col route, which involves establishing a series of high camps over a period of two months. We gathered data from the climbers at Base Camp (altitude 5,300 m) before and after the ascent to the higher camps, at Camp Two (6,300 m), and at Camp Three (7,150 m). Conditions at Camp Four (8,000 m) or higher (e.g., weather conditions and communications quality) made testing problematic, particularly voice recordings. No data from locations higher than Camp Three are reported.

Supplementary oxygen was not used below Camp Four. All testing sessions were held within a day of reaching each location. Final testing at Base Camp was done after a descent from the summit for four subjects; one subject who decided to forgo a summit attempt was tested after his descent from Camp Four. The experimenters remained at Base Camp throughout the expedition, where they recorded speech samples transmitted from the climbers. Motorola hand-held Sabre radios (5W RF output), Max-Trax base station radios (20W RF output), and Sony NT-1 digital micro DAT recorders were used throughout the project. Sampling with the NT-1 DAT recorder was done at 27 KHz using 12-bit logarithmic quantization equivalent to 16-bit linear. The signals were resampled for computer analysis at 20 KHz using 12-bit linear quantization. The digital recording established an accurate time base for the VOT measurements.

Speech measurements

Speech samples for the VOT analysis were obtained by asking each subject to read 60 English monosyllabic words (a 30 word list read twice) that had voiced and unvoiced stop consonants in initial position and final position, e.g., *bat*, *kid*, etc. VOT was subsequently measured at Brown University using an interactive computer-implemented system. Cursors were placed on the onset of the burst produced on the release of each word-initial stop consonant and at the onset of phonation, by means of both visual inspection of the waveform and by listening to marked portions of the signal.

VOT measurements from all three places of articulation (i.e., labial [b] and [p], alveolar [d] and [t], and velar [g] and [k]) were combined by aligning their perceptual boundaries.[1] The *separation width*, i.e., the distance (in time units) between the longest voiced VOT and the shortest unvoiced VOT, was measured for each subject at each location. Deterioration in motor control is manifested by reduced separation width; in cases of severe impairment the voiced and unvoiced regions might overlap and the separation width would become negative.

Syntax testing

A 50 sentence version of the RITLS was administered at each location. Each version included 25 simple and 25 complex sentences balanced for vocabulary, sentence length, and syntactic patterns. RITLS test booklets containing the sketches corresponding to the sentences were carried to the higher Camps. The test was administered by showing the subject a page which presented three elaborated line drawings, one of which best exemplified the meaning of the sentence that was then read aloud by the experimenter. For example, for the sentence "The man is watching the girl who is in the water" the choices were (1), a man and a girl on the sand, (2), a man on the sand and a girl in the water, and (3), a man in the water and a girl on the sand. The subject then responded by announcing the number of the sketch that best exemplified the meaning of the sentence.

Before each sentence the subject announced the page number he was looking at to indicate that he was ready and to verify that he was looking at the correct drawings. The test sentences, which were read aloud by the experimenter, and the subject's vocal responses were tape recorded. The response time was determined by a single listener by measuring with an electronic stopwatch the time interval between the end of each spoken sentence and the subject's response. Multiple measurement of several sample trials showed that such measurements were consistent within 0.1 s.

Cognitive testing

Three cognitive tests were also administered to subjects at each location, to test attention and concentration, expressive language and structured response initiation, and maintenance and shifting of cognitive sets (Parkinson's study group, 1989). The confrontation "naming" test, sometimes referred to as the verbal fluency test, tested the subjects' ability to generate words beginning with particular letters of the alphabet. The subject was presented with a letter and was asked

[1]For a given set of VOT measurements and a "boundary" point on the VOT axis, the corresponding "perceptual overlap" is the percentage of VOT measurements on the "wrong" side of the boundary, with a 10 ms tolerance, i.e., the sum of all voiced VOTs greater than 10 ms less than the assumed boundary plus the sum of all unvoiced VOTs less than 10 ms greater than the assumed boundary divided over the total number of VOT measurements. The perceptual boundary is defined as the boundary point for which perceptual overlap is minimized; if there is a region of minimum overlap the perceptual boundary is set at its midpoint.

Table 1
Separation width (in milliseconds) between longest voiced VOT and shortest unvoiced VOT for each subject at each location with the three places of articulation combined (BB=Base Camp before the climb, C2=Camp Two, C3=Camp Three, BA=Base Camp after the climb).

	Location			
Subject	BB	C2	C3	BA
1	30	26	13	29
2	22	14	6	7
3	32	8	8	20
4	14	13	-10	16
5	22	-3	10	23

to produce as many words as possible in one minute, excluding proper nouns; this was repeated with two more letters, for a total of three letters at each location. Different letters were used at each location. The subject's score was the total number of words produced for all three letters.

The digit-span tests tested the subjects' ability to repeat a sequence of numbers in the order presented (forward digit span) and in the reverse order (backward digit span). To administer this test the experimenter read aloud a sequence of digits, starting with a sequence of three digits. The subject had to immediately repeat the digits in the same order; this was repeated once more with another sequence of the same length. If the subject correctly repeated at least one of the two sequences the process was continued with two sequences of length greater by one. When the subject failed to repeat both sequences of a given length the test was terminated and the subject's score was the total number of sequences reproduced correctly. Then the same process was repeated (with different sequences, starting with a sequence two digits long) but this time the subject was required to reproduce the sequence in reverse order.

Finally, the odd-man-out test tested the subjects' ability to form and then shift abstract categories. A test booklet, carried up to Camps Two and Three, contained on each page a set of three figures, one of which shared a feature with each of the other two. For example, there was a page with a large oval, a small oval, and a large triangle. The subject's task was to form a criterion (e.g., either size or shape) and to pick the "odd" figure on each page according to that criterion. After this first sort the subject was asked to sort the same set of figures using another criterion. Subjects were not told what the possible criteria were. The total number of errors (in both sortings) for each subject were counted.

In addition to these tests, the expedition maintained a log book noting each day's activities. The experimenters noted any incidents that appeared to exemplify poor judgement on the part of the climbers.

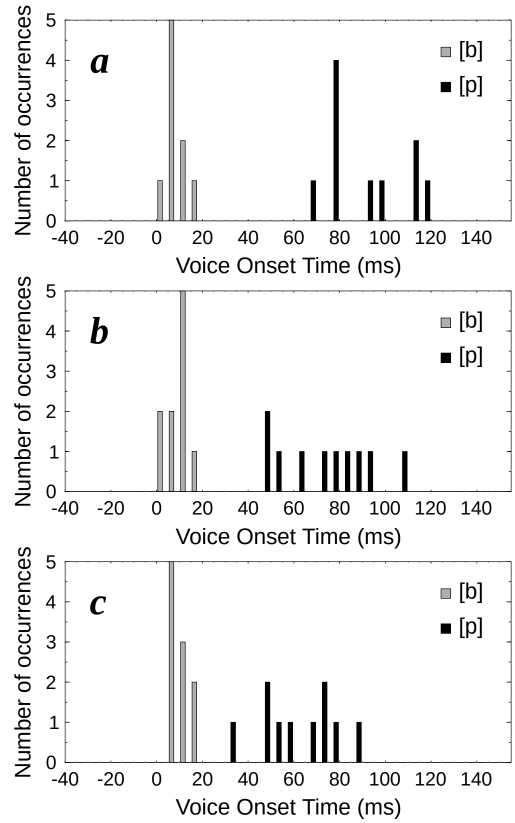

Figure 2. Number of VOT measurements per 5 ms bin. (a) VOTs for Subject 1's labial stop consonants ([b]s and [p]s) at Base Camp before the climb. Note that the [b]s cluster between 0 and 20 ms, whereas the [p]s occupy a distinct range after 70 msec. The separation width is about 52 ms, so the [b]s can be readily distinguished from the [p]s by virtue of the VOT distinction. (b) VOTs for Subject 1's labial stop consonants at Camp Two. Note that the separation width has decreased to 26 ms. (c) VOTs fot Subject 1's labial stop consonants at Camp Three. The separation width for these consonants decreased to 13 ms, thus (given a perceptual tolerance of about 20 ms) preventing absolute differentiation between [b] and [p] on the basis of VOT only.

Results

Table 1 shows the separation width of each subject's VOTs on each location for all places of articulation combined. Note that there is a wide VOT separation at base camp, but the distinction becomes less pronounced at the higher camps. This drop is illustrated in Figure 2, where the labial stop VOTs of Subject 1 occupy two distinct, well separated, regions at Base Camp before the climb (2a) but are less separated at Camp Two (2b) and even less so at Camp Three (2c). In some instances, separation decreased considerably at the higher camps, and even overlap occurred.

The subject averages are plotted in Figure 3. Analysis of variance showed a significant effect of location ($F(3,12)=6.30$, $p<0.008$). Pairwise contrasts showed that the differences between Base Camp before the climb (24.0

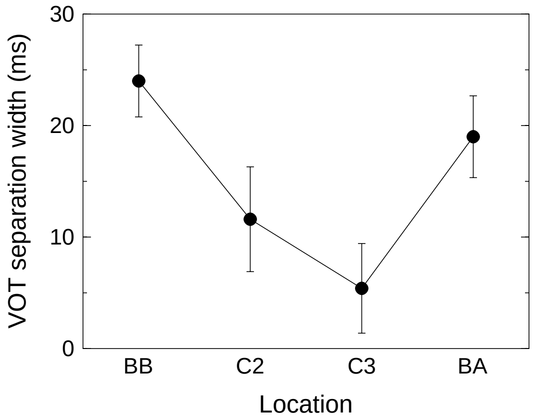

Figure 3. Mean VOT separation width for five subjects at four locations (BB=Base Camp before the climb, C2=Camp Two, C3=Camp Three, BA=Base Camp after the climb). Error bars show standard error.

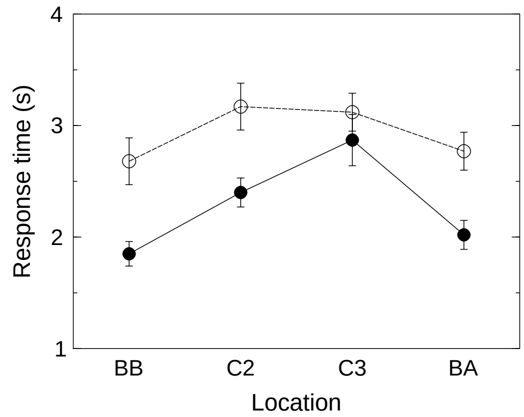

Figure 4. Mean response time to the simple (•) and complex (○) sentences of the RITLS for four subjects at four locations (BB=Base Camp before the climb, C2=Camp Two, C3=Camp Three, BA=Base Camp after the climb). Error bars show standard error.

ms) and Camp Three (5.4 ms), and between Base Camp after the climb (19.0 ms) and Camp Three were significant ($F(1,4)$=62.22, $p<0.001$, and $F(1,4)$=11.52, $p=0.027$, respectively); the difference between Base Camp before the climb and Camp Two (11.6 ms) was marginally significant ($F(1,4)$=5.99, $p=0.071$). Note that the mean separation width at the higher camps is less than the normal 20 ms which are considered necessary for our perceptual system to unambiguously perceive the categorical distinctions between “voiced” and “unvoiced” stop consonants.

The mean response time (RT) to the RITLS items is shown in Table 2, separately for the simple and the complex sentences. Note that RT increases at the higher camps, indicating an increased difficulty in syntactic processing. Figure 4 plots the subject averages for four subjects[2] at all locations. Analysis of variance showed significant main effects of complexity ($F(1,3)$=22.57, $p=0.018$) and of location ($F(3,9)$=5.11, $p=0.025$) but no interaction ($F(3,9)$=0.95, $p=0.455$). In analyses of variance separately for simple and for complex sentences, there was a significant effect of location on simple sentence RTs ($F(3,9)$=10.18, $p=0.003$) but not on complex sentence RTs ($F(3,9)$=0.95, $p=0.458$). Pairwise contrasts using only RTs to simple sentences showed a significant difference between Base Camp before the climb (1.85 s) and Camp Two (2.40 s, $F(1,3)$=44.34, $p=0.007$) and between Base Camp before the climb and Camp Three (2.78 s, $F(1,3)$=46.33, $p=0.006$). The drop in response time after returning to Base Camp (i.e., between Camp Three and Base Camp after the climb) was marginally significant ($F(1,3)$=7.63, $p=0.070$).

The Pearson product-moment correlation coefficient between the subjects’ response time to simple sentences and their VOT separation width was -0.774, (significant to $p=0.0001$), which means that one can account for 60% of the syntax comprehension variance by the VOT measure.[3]

The total number of words generated by each subject in the confrontation naming task, shown in Table 3, was not significantly affected by testing location ($F(3,12)$=1.14, $p=0.37$). The individual subjects’ performance on the digit span tests was unaltered throughout the experiment ($F(3,12)$=1.06, $p=0.40$); the subjects’ scores are shown in Table 4. Almost no errors were made on the odd-man-out test except for Subject 4 after a respiratory infection on the mountain. His error rate was 30% on the second trial at Base Camp after he had returned from Camp Four; VOT overlap also occurred after this infection.

Several episodes occurred in which subjects’ judgement was remarkably compromised. For example, Subject 4 (whose VOTs overlapped at Camp Three) advocated climbing in extreme avalanche conditions and was only dissuaded after vehement discussion. Another climber would have fallen into a wide crevasse that he was about to jump unroped had a Sherpa not intervened.

Discussion

We have found a significant effect of altitude on VOT separation width and on simple sentence comprehension response time. In agreement with Regard et al. (Regard et al.,

[2]Data for Subject 2 at Camp Three are missing because of a recording error. Using the mean value of the other four subjects’ RTs at Camp Three gives similar results in all statistical tests reported here.

[3]The data of Subject 2 for three locations were included in the correlation; leaving them out made no difference ($r=-0.776$, $p=0.0004$).

Table 2
Mean response time (in seconds) to the RITLS sentences by subject and location, separately for the simple and the complex items of the test.

	Base Camp, before		Camp Two		Camp Three		Base Camp, after	
Subject	Simple	Complex	Simple	Complex	Simple	Complex	Simple	Complex
1	1.47	2.75	1.93	2.53	2.34	3.36	2.17	2.65
2	1.93	3.19	2.48	2.73	(*)	(*)	2.36	2.52
3	1.99	3.28	2.37	2.91	3.37	2.97	1.96	3.27
4	2.10	3.03	2.72	4.07	3.18	3.18	2.37	3.40
5	1.83	1.66	2.57	3.17	2.59	2.97	1.56	1.78

*These data are missing because of a recording error.

Table 4
Digit span (total number of sequences correctly repeated) forward and backward for all five subjects at all locations.

	Base Camp, before		Camp Two		Camp Three		Base Camp, after	
Subject	Forward	Backward	Forward	Backward	Forward	Backward	Forward	Backward
1	10	5	9	2	10	5	10	9
2	13	5	13	11	13	10	12	11
3	8	8	5	6	6	8	6	8
4	6	5	7	5	8	5	7	4
5	8	7	11	5	6	6	12	10

Table 3
Total number of words generated for three initial letters in the confrontation naming test, five subjects at four locations (BB=Base Camp before the climb, C2=Camp Two, C3=Camp Three, BA=Base Camp after the climb).

	Location			
Subject	BB	C2	C3	BA
1	28	27	16	28
2	28	35	28	30
3	29	25	(*)	26
4	22	30	24	22
5	27	25	29	30

*These data are missing because of a recording error.

1991), who used similar tasks, no effect was found for the digit span, the confrontation naming, or the odd-man-out test. The observed deficits appeared to be temporary, since performance improved upon return to Base Camp. This finding is consistent with previous studies that have found no persistent impairments after a high altitude expedition (Clark et al., 1983; Jason et al., 1989). Hornbein et al. (Hornbein et al., 1989) also reported intact performance in the digit span test after a simulated ascent to 8,848 m.

We conclude that hypoxia, caused by low concentration of oxygen in the air, caused subjects' neural functioning at high altitude to depart from normal, at least in the regions of the brain involved with syntax comprehension and speech motor control. Complex sentences were found to take more time than simple sentences to process, therefore reaction time can be used to assess processing difficulty.[4] The increase in response time to the simple sentences at higher altitudes, indicating greater processing difficulty, suggests that the climbers' neural functioning is considerably compromised. Note that 10 year old children have no problem understanding any of the RITLS sentences. In this light, it may be less surprising that climbers and pilots have often reported impaired judgement at high altitudes. The fact that the similar trend of response times to complex sentences is not significant may be due to the small number of subjects studied. Alternatively, it is possible that complex sentences, because of their embedded clauses, may make heavy demands on processing resources that are already impaired at Base Camp.

The small number of subjects tested may have affected the power of our statistical tests. However, apart from the effect of altitude on response time to the complex items of the RITLS, there is no clear trend in any of the other tests. Therefore, it is not very likely that the lack of statistical significance is a result of the small number of subjects; a genuine lack of effect of the factors tested seems more likely.

[4]Regarding reaction times in hypoxic situations, Fowler & Kelso (Fowler & Kelso, 1992) reported a slowing of "the preprocessing state of stimulus evaluation." Their findings do not apply to our situation because they were for responses to visual stimuli, whereas earlier studies had found little effect of hypoxia on the latency of evoked potentials for auditory stimuli (Deecke, Goode, Whitehead, Johnson, & Bryce, 1973). Moreover, if the increased RTs in our tests were due to some general slowing of responding it should have been identical for simple and complex sentences.

This null result leads us to the conclusion that some tasks were unaffected at high altitudes. Practice effects, although probably playing some role in the subjects' performance at the higher camps, cannot alone account for the observed pattern of results. If subjects were improving at the experimental tasks and this improvement was offset by cognitive slowing down at the high camps, one would expect a small or no significant effect of altitude during the ascent, as observed, and a substantial improvement at Base Camp after the climb to the summit, which is not consistent with our findings. Alternatively, there may have been no such improvement upon return to Base Camp because of some longer lasting deficit caused at high altitude. Such a hypothesis is neither supported by others' findings with similar testing nor by the improvement in RITLS simple items response times upon return to Base Camp. Although one should be cautious when interpreting statistical tests with small *N*, particularly when referring to cognitive functions (notoriously variable between individuals), the overall pattern of our findings indicates that cognitive impairments when climbing to high altitude are selective and temporary.

Other factors that might have caused the observed deficits in VOT and syntax comprehension, such as temperature, fatigue, and alcohol intoxication, can be easily ruled out. Although temperature occasionally fell to $-40°$C, the test sessions were conducted at Base Camp at moderate temperatures (15–25°C) and at Camps Two and Three in tents by climbers wearing down climbing suits or immediately outside their tents in sunny, warm, windless conditions. General fatigue cannot account for the observed pattern because the tests administered upon return to Base Camp were conducted just after the climbers had completed the most strenuous part of the climb (a minimum of 16 hours in continuous activity ascending from Camp Four to the summit and back before descending to Camp Two and to Base Camp), yet VOT separation width was larger and RITLS response time was shorter than at the higher Camps. Alcohol intoxication affects speech production to such an extent that speech measurements have been proposed to evaluate sensory and motor impairments due to alcohol consumption (Brenner & Cash, 1991; Pisoni & Martin, 1989). However, no alcohol was ingested by any of the subjects while they were at Camps Two and Three or before the test sessions at Base Camp.

Hypoxia, selectively affecting some brain structures, remains the most likely cause of our findings. Acclimatization would have been minimal at testing time because subjects were tested at Camps Two and Three upon arrival at those altitudes. Furthermore, acclimatization is incomplete at these altitudes; it is unclear whether any improvement occurs for longer stays above 6,000 m (West, 1985).

Exposure to extreme altitude does not appear to affect all aspects of cognitive behavior to the same degree. Long-term memory, for example, was not affected in a previous study at Everest Camp Two when it was not combined with learning (Nelson et al., 1990).[5] The pattern of deficits noted at extreme altitude is, therefore, consistent with other studies that indicate that the neural bases of long term memory and the lexicon appear to be dissociable from those regulating speech motor control and syntax. Speech motor control and syntax, for example, are preserved in Alzheimer's disease which affects lexical ability and memory (Kempler, Curtiss, & Jackson, 1987; Kempler, 1988). In contrast, long term memory and lexical ability are preserved in non-demented Parkinson's patients who show syntax comprehension and VOT motor control deficits (Lieberman et al., 1992).

It is possible that the VOT and syntax comprehension deficits we report here have a similar neurological basis to Parkinson's disease, i.e., they may reflect the degradation of basal ganglia pathways to prefrontal cortex. Similar patterns of deficits have been found in patients with Parkinson's disease, where the main pathological findings are compromised cells in the basal ganglia, particularly in the substantia nigra, and throughout the dopaminergic pathways in the lentiform and caudate nuclei to the prefrontal cortex (Cummings, 1993; Parent, 1986). Non-demented Parkinson's patients tested with these tasks have shown small decrements in digit span and confrontation naming performance in contrast to high RITLS error rates. They also show speech motor control deficits evidenced in VOT measurements (Lieberman et al., 1992). Although the extent of the deficits of Parkinson's patients is much larger than that of our subjects the pattern is strikingly similar. The severity of the deficits cannot be expected to be comparable, because Parkinson's patients may have profound impairments whereas individuals fit enough to climb Mt. Everest cannot possibly be very severely impaired.

An important theoretical implication of the correlation between the impairments in speech motor control and in sentence comprehension is that it is not consistent with the "syntax module" advocated by some researchers (e.g., (Pinker, 1994; Wilkins & Wakefield, 1994)). That is, unless speech motor control and syntactic deficits are dissociable, the argument for a brain structure specialized for syntactic processing is empirically unsupported. The observed correlation may reflect the preadaptive role of speech in the evolution of syntax (Lieberman, 1991, 1992).

Apart from its theoretical importance for neural and linguistic theories, this correlation can also have practical applications. Cognitive impairments have been frequently observed in high altitude climbing and flying and have often led to accidents due to improper evaluation of danger or other

[5] It must be noted that other studies have found memory deficits (Regard et al., 1989, 1991; Cavaletti et al., 1987), but not with identical tasks; the length of exposure to high altitude and the actual altitude also have varied between studies. Furthermore, as Nelson et al. (Nelson et al., 1990) have pointed out, memory testing in which impairments were observed had included a learning component.

poor judgement (Ward et al., 1989; Nelson et al., 1990). If syntax comprehension deficits, such as those we observed, are a good index of the other cognitive impairments then our findings suggest that speech motor control, as measured through VOT separation width, can provide an estimate of the extent of the impairment. Thus, we can construct a remote monitoring system to automatically measure VOT separation width in naturally occurring speech (e.g., for communication) to assess neural functioning of personnel involved in hazardous situations where the consequences of error can be grave, such as aeronautics, spaceflight, and flight control.

Initial applications will certainly include situations not only of hypoxic hypoxia but also of anaemic hypoxia (e.g., from carbon monoxide intoxication), because the same brain structures are again the most sensitive (globus pallidus in the basal ganglia, hippocampus, and parts of the substantia nigra (Brierley, 1976; Laplane et al., 1989)) and perhaps of alcohol intoxication, if a similar relationship holds between speech motor control and the extent of the impairment. Furthermore, it will be possible to use similar methods to remotely evaluate the treatment of neurodegenerative diseases such as Parkinson's. A patient would just make a phonecall and an automated speech analysis system could aid the physician to evaluate their progress and adjust the treatment accordingly.

Conclusion

We have found correlated deficits in speech motor control and syntax comprehension in five subjects climbing Mt. Everest. These deficits were more pronounced at higher altitudes; no deficits were found in other cognitive tasks, yielding a pattern similar to that found in Parkinson's patients. We argue that the impairments are due to disruption of basal ganglia pathways to prefrontal cortex caused by hypoxia, in agreement with neuropathological findings on the vulnerability of brain structures. The theoretical implications of our findings are in favor of a basal ganglia involvement in many functions besides motor control and not consistent with a specialized syntax module in the brain.

The practical applications of our study are also very important. Previous studies have identified various cognitive impairments in climbers at high altitudes, but have not offered a practical way to remotely assess their neural functioning. While symptoms of acute mountain sickness (Regard et al., 1991) and ventilatory response (Ward et al., 1989) have also been reported to correlate with cognitive performance, the former is not useful in prevention and the latter is far less easy to monitor than VOT separation width in speech that is readily available from the communications channels.

More research is necessary to refine and validate the procedure we propose, and to build a compact automatic speech analysis system for remote monitoring. Such systems may become indispensable in various situations where monitoring crew behavior is critical, as well as in the day-to-day treatment of Parkinson's disease.

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