ENVIRONMENTAL COMPLEXITY: INFORMATION FOR HUMAN-ENVIRONMENT WELL -BEING

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We investigate the importance of environmental complexity as a factor influencing cognitive function and well-being of the elderly. Environmental complexity was calculated based upon an estimate of the number of visually distinct environments characteristic of the objects in five photographs of each elderly subject's home. It was found that more complex environments correlated with the higher cognitive function and more robust locomotor activity of those living in the community. Complexity was found to be a quality of the environment independent of aesthetics.

1. Overview

The concept of complexity plays an important role in informal discussions of our environment and in formal arguments in the study of complex systems. We believe it is important to demystify the concept of complexity and develop it as a quantitative measure of systems and environments. A quantitative measure that can be usefully applied in the social sciences must be readily applied to real world observations. A central conceptual difficulty in applying abstract notions of complexity to real world systems is realizing that we must distinguish between unobservable (e.g. microscopic) patterns and observable (e.g. macroscopic) patterns. To evaluate the complexity of a system/environment for a particular observer we must consider only the patterns that the observer can distinguish. A specific approximate measure of the complexity of a visual environment provides a means to examine the human experience of complexity. Our immediate research target is to understand the effect of environmental complexity on elderly individuals. A measure of environmental complexity can quantify the notion of sensory stimulation / deprivation and its effects on the maintenance of cognitive function.

2. Background

We investigated the possibility of a correlation between environmental complexity and measures of cognitive function, well-being, and locomotor activity. The motivation for the study was the observation by environmental researchers that while order is important so that people can make sense of the environment, the environment need not be simple; rather a moderate amount of complexity is preferred and contributes to the ability of elderly individuals to maintain activity and mental alertness [Berlyne 1971, Lawton 1981, Mandell & Schlesinger 1990]. Environmental change can force an individual to alter existing patterns and shift to new ones, a process that could stimulate the maintenance and development of the neuromuscular system. Mandell and Schlesinger [1990] noted that with aging a decline in brain stem reticular (activating) neurons results in a decrease in the rich variety of impulses seen in younger persons and suggested that the environment might be a resource for maintaining a high degree of neural complexity and cognitive function. They hypothesized that an environment sufficiently complex to offer choices may prolong a high quality of life. In contrast, an environment arranged to provide order and comfort may remove much of the challenge of disorder and, thereby, stimuli essential to the generation of diverse neuronal impulses and the subsequent maintenance of cognitive function and well-being. From his studies of human brains, correlating the development of dementia with intellectual ability and life-time habits, Snowdon [1998] concluded that mental exercise maintains mental functioning, similar to the effect of physical exercise on muscular health. Patterns of usage appear to justify which aspects of physiology to maintain, and complex patterns are likely to be necessary for complex functioning. This is a natural consequence of adaptation to complex or simple environments.

Measures of complexity have become important in the study of physiologic response through studies of heart rate dynamics [Goldberger, 1997]. These studies are based upon estimates of the complexity such as approximate entropy (ApEn) and the scaling behavior of the autocorrelation function. The latter measure shows that fluctuations exist on many different time scales in the heart beat interval in healthy young individuals. Such fluctuations are necessary to allow the system to change in response to environmental change on the same time scales [Bar-Yam, in preparation]. Disease [Goldberger, 1997] and aging [Iyengar, Peng, Morin, Goldberger & Lipsitz 1996] lead to progressively simpler heart rate time series indicating a lack of ability of the system to respond to environmental changes. In the extreme, the system can become periodic, repeating behavior in a predictable and non-adaptive fashion. More generally, a physiologic system that has lost complexity becomes less able to respond to an uncertain and continuously changing environment to maintain its own functioning. The question arises "How can the complexity of the physiologic system be maintained?". This study was predicated by the assumption that the exercise of psycho-physiologic function through appropriate on-going environmental complexity can serve an important role in the maintenance of psycho-physiologic complexity and of well-being. In order to investigate this assumption, we introduce an approximate measure of environmental complexity which can serve like the approximate measures of physiological complexity to guide our understanding of environment - system interactions.

Figure 1: Examples of photographs of study participants living rooms and the related estimated complexities.

Participant #1's Living Room
Quantitative Complexity 1336

Participant #15's Living Room
Quantitative Complexity 224

Living Room: Quantitative Complexity

Object Type	Number	Complexity
Clock	1	17
Window	1	46
Tables	3	34
TV	1	35
Pictures	3	62
Sm Objs	31	875
Papers	5	150
Books	4	117
Total		**1336**

Living Room: Quantitative Complexity

Object Type	Number	Complexity
Stand	1	11
Window	1	44
Lamp	1	11
TV	1	45
Couch	1	24
Drapes	1	8
Pictures	5	75
Carpet	4	6
Total		**224**

3. Study Design

A variety of approaches to quantifying the complexity of physical systems exist [Bar-Yam 1997]. Our quantitative measure of complexity was based upon Shannon’s theory of information [1948/1963] and the concepts of Kolmogorov complexity [Li & Vitanyi 1993]. In Shannon's theory [Pierce 1980] the amount of information (for example, in a message transmitted between two individuals) increases as the number of possible messages increases and decreases as the number of possible messages decreases. A greater set of possible messages corresponds to a greater uncertainty on the part of the recipient as to the message content and a higher information content in the message. Algorithmic complexity allows regularities or patterns in a message to be recognized. These patterns reduce the information contained in the message by causing it to be more predictable, reducing the uncertainty. Gell-Mann [Gell-Mann, 1995, p.17; Gell-Mann and Lloyd, 1996] defined the descriptive complexity of physical systems as the "length of concise description of a set of the entity's regularities". It is important to recognize that measurement of the complexity of physical systems depends on the scale at which differences in the state of the system are significant. Some may focus on the microscopic complexity of a system, distinguishing different positions of atoms, but it is also possible to consider the differences seen by a social observer as relevant to counting possible states of the system [Bar-Yam 1997]. We can think about the problem of evaluating the complexity of a system as one of counting the number of distinguishable states of the system which are in the same class of states, where the class itself is defined relative to an observer. The information is defined as the logarithm of the number of states, because the number of descriptions is exponentially related to the length of a description (e.g. a string of characters).

For this study, the complexity of the environment of an elderly individual was determined by estimating the number of visually distinct environments (states of the system) that were possible given the objects in the environment. Since the placement of one object is often independent of the placement of other objects, the number of possible environments is the product of the number of possible distinct locations of each object. For example, if there are two objects in the room, and each of them has n possible locations, then the total number of possible arrangements is n^2. By the properties of the logarithm, the information necessary to specify the locations of all the objects in an environment is the sum of the information necessary to specify each of the objects. For the same example, the total information to specify the location of both objects is $\log_2(n^2) = 2\log_2 n$. More generally, if there are a number of objects of a similar type, the number of objects multiplies the complexity of each of the objects to obtain the complexity of the environment. As a consequence, the complexity of the environment is typically dominated by a simple count of the number of objects in the environment. Intuitively, this corresponds to our understanding of environmental complexity, since a bare environment is simple, while a cluttered environment is complex. See Figure 1 for a contrast between living rooms with high and low complexity.

3.1. Subjects and Data Collection

The 32 study participants lived in either private community residences (n=14) or in congregate housing for the elderly (n=18) - separate apartments with common dining and sitting room areas - in twelve suburbs of Boston. The participants were randomly selected either from an academic institution’s registry of persons over 65 years of age willing to participate in research or from those indicating a willingness to participate during recruitment presentations in congregate housing developments. Subjects were pre-screened by telephone for functional health problems (e.g. an uncontrolled chronic illness or seriously impaired vision or hearing). For those found to be healthy, a home interview and return visit three days later was scheduled during this initial contact. Only one person declined to participate.

Participants ranged from 67 to 96 years with no significant difference found between settings (Community mean = 77.43 years, Congregate mean = 78.88 years). The two groups of subjects were very similar in marital status, class, race, sex, and education. Hypertension (8) was the most common reported illness, with anti-hypertensives (10) the most commonly taken medication.

Data were collected from November to May with approximately equal numbers from community and congregate dwellers interviewed each month. At the first visit, the interviewer obtained written consent, explained the testing procedure, administered the instruments, asked the participant what they liked and disliked about their environment, and placed an activity monitor on the participant's wrist with instructions to wear it continuously (except for bathing or intense exercise) for three days. Photographs were taken as the investigator accompanied the person about their interior and exterior environment.

3.2. Measures of Complexity

Qualitative Measure of Environmental Complexity. The measurement of environmental complexity was based upon five Polaroid photographs of each participant's environment: 1) living room, 2) kitchen, 3) and 4) other interior rooms of their space (usually dining and bedroom), 5) outdoor environment frequently visited. The photographs were assessed qualitatively for complexity and degree of aesthetic appeal by using a panel of a lay person and three environmental experts (an architect, interior designer and environmental researcher). The evaluators were asked to rate each photograph on both the degree of 1) complexity and 2) aesthetic appeal using two 100 mm visual analog lines (VAL). The first VAL had anchor points of "Not at All Complex" (0) and "Extremely Complex" (100) and the second VAL had anchor points of "Not at All Aesthetic" (0) and "Extremely Aesthetic" (100). A mean for complexity and aesthetics was calculated for each participant by averaging the four raters' VALs. We note that this measure is a semi-quantitative measure of complexity based upon rater intuition.

Quantitative Measure of Environmental Complexity. The same five photographs were used to estimate the quantitative complexity using information theory formalized by counting the number of distinct possible environments. The number of possible positions (locations) and rotations (orientations around their own axes) was estimated by considering those which would be visually distinct in the context of the environment. Some subjectivity in counting possibilities or estimating complexities is acceptable since, ultimately, we are interested only in differences between the complexity of the environments. Therefore, consistency of measurement is more important than the absolute values of the numbers obtained. Thus, the position of a chair in the room was considered distinct if it could be displaced about a foot in either of two Cartesian directions. An object on a table was considered confined to the top of the table but could be moved around on it, unless it was placed at one of the corners. For the counting, it is only necessary to consider locations that are likely and improbable locations, such as placing pictures on the ceiling, were not considered. A more precise definition of Shannon's Information theory that allows different probabilities may be written as:

$$I = -\sum P(i) \log_2 P(i)$$

where P(i) is the probability of a particular location and the sum is over all possible locations. This reduces to the previous expression based on the number of possibilities when each location has equal probability.

While the dominant influence on complexity tends to be a count of the number of simple objects, we also made an estimate of the contribution to environmental complexity of the internal structure of objects. This was specified by describing several object attributes: shape, texture, motion, and pattern. These properties contribute independently (i.e. multiplicatively) to the number of possibilities of the object and thus additively to the complexity of the environment. Care was taken to avoid double counting (e.g. shape and rotation) contributions to the complexity. Approximate numerical values were assigned to indicate the complexity of each object attribute. The shape can vary from a primitive shape (circle, triangle, square) to one with many curves and angles. Texture can range from flat and smooth to a rough and varied surface. Motion may vary from stationary to dynamic - a rocking chair, plant, or television. Internal pattern can range from one solid color to a multi-colored weaving composed of many discernible small patterns. The estimates of object attribute complexity are the most roughly estimated aspects of the quantitative measure. However, this is reasonable in that object complexity differences affect the total complexity only weakly. The complexity of each object was then multiplied by the number of objects of the same type. The result was then summed over all types of objects to obtain the complexity of a particular room. Room complexities were then added to obtain the total complexity of the environment of an individual. Table 1 shows the calculation for the photograph in Figure 1 (left side). Note that in this case, the number of objects is large and the complexity is large. However, the number of possible positions for each object is limited because of the existence of many other objects occupying space in the room.

Table 1. Complexity Calculation for Photograph of Participant #1's Living Room
The caculation of the complexity for a particular object type corresponds to the expression: Number of objects x ($\log_2$ Positions + $\log_2$ Rotations + Shape + Texture + Motion + Pattern) = Complexity of Object Type.

Object Type	Number of Objects	Positions	$\log_2$ P	Rotations	$\log_2$ R	Shape	Texture	Motion	Pattern	Complexity of object	Complexity of object type
Clock	1	10	3.3	24	4.6	2	1	4	2	16.9	16.9
Window	1	4	2	8	3	10	2	9	20	46.0	46
Tables	3	20	4.3	2	1	2	2	0	2	11.3	34
TV	1	5	2.3	4	2	2	1	8	20	35.3	35
Pictures	3	20	4.3	10	2.3	2	1	0	10	20.6	62
Sm objs	31	20	4.3	15	3.9	8	2	0	10	28.2	875
Papers	5	20	4.3	6	2.6	2	1	0	20	29.9	150
Books	4	20	4.3	4	2	2	1	0	20	29.3	117
Total Complexity for Living Room of Participant 1						(Sum of complexities of all object types) = 1336					

3.3. Measures of Well-Being

Mental well-being. The Brief Psychiatric Rating Scale [BPRS; Overall & Gorham 1962] was used to measure mental well-being and supplemented by the Symptom Questionnaire [SQ; Kellner 1987], which is a self-report (yes/no) questionnaire that provides information on depression, anxiety, somatization, and irritability, along with wellness scales for happiness, contentedness, physical health, and friendliness. Cognitive well-being was assessed by the Mini-Mental Status Exam [MMSE; Folstein et al 1975].

Locomotor Activity. Levels of locomotor activity were quantified using a wrist worn ambulatory activity monitor. The Mini MotionLogger is manufactured by Precision Control Design, and distributed by Ambulatory Monitoring Inc. [Ardsley, N.Y.]. Only slightly larger than a typical wrist watch (1.5" x 1.3" x .38") it was worn on the non-dominant wrist day and night except for bathing or extreme exercise. A piezoelectric bilaminar bender or accelerometer detected all movements greater than 0.01 g force, collecting data in one minute epochs over 3 days. Locomotor activity was analyzed for mean levels of activity, magnitude and timing of circadian rhythms [Teicher & Barber 1990], and degree of complexity. Sleep efficiency was inferred from the ambulatory activity records using sleep continuity algorithms. The algorithm developed by Cole et al [1992] distinguished sleep from wakefulness 88% of the time and correlated sleep efficiency (0.82) and sleep latency (0.90) respectively with polysomnograph scoring.

4. Findings

The calculated quantitative complexity of the environment ranged widely between 914 and 19,046. The simplest environment with a total complexity value of 914 was solid white and tan with little pattern, no ornamentation, few objects and pictures, and no plants. The 19,046 value environment had many colors, patterns, objects, books, pictures and plants that could easily be moved to different arrangements. The existence of a wide range of environmental complexities indicates that the estimates obtained were not sensitive to details of the estimation process. The complexity value was typically dominated by a count of the number of small objects found in the environment. A specific enumeration of the complexity of each of the objects provides an increased confidence in the reliability of this measure. Participants living in the community had more complex environments than the congregate dwellers both quantitatively ($p = 0.022$) using the objects analysis and qualitatively (p = 0.007) using the VALs. Mean Qualitative Complexity VALs ranged from 15 to 34 and mean Aesthetics VALs from 16 to 30. However, the VAL ratings of aesthetic appeal were very similar (Community = 23.17; Congregate = 22.17) and not significantly different (Table 2).

Table 2. Complexity of Environment: Quantitative and Qualitative

Variables	Community	Congregate	f	p
Quantitative Complexity	5230 ± 800	2660 ± 700	5.82	0.022
Qualitative Complexity	27.1 ± 1.0	22.8 ± 0.9	8.26	0.007
Aesthetics	23.0 ± 1.1	22.2 ± 1.0	0.45	0.508

4.1. Well-Being

Cognitive Function. The cognitive functioning (MMSE) scores ranged from 24 to 30 and were significantly higher for those living in the more complex environment of the community (p = 0.034). There was no significant difference between the groups in mental well-being as measured by the BPRS or any of the four components of the Symptom Questionnaire (Anxiety, Depression, Somatization and Hostility) (see Table 3). These findings support the first hypothesis that the elderly living in more complex environments have greater cognitive functioning, but not the second hypothesis, that they would also have greater mental well- being.

Table 3. Cognitive Function and Mental Well-Being of Participants
(note: Higher scores indicate more abnormal mental well-being for BPRS and SQ)

Variables	Community	Congregate	f	p
Cognitive Function (MMSE)	29.5 ± 0.9	28.5 ± 1.5	4.95	0.034
Emotional Well-Being (BPRS)	19.1 ± 0.8	20.4 ± 0.7	1.58	0.220
Anxiety-Symptom Quest. (SQ)	3.9 ± 1.1	2.9 ± 1.0	0.44	0.513
Depression (SQ)	4.3 ± 1.3	3.3 ± 1.2	0.33	0.568
Somatization (SQ)	3.5 ± 1.0	5.4 ± 0.8	0.03	0.862
Hostility (SQ)	2.1 ± 0.8	2.3 ± 0.7	0.016	0.900

Circadian Locomotor Activity. Participants living in the more complex environment of the community showed significantly greater circadian locomotor activity (time series data collected with the wrist monitors) than congregate dwellers (see Table 4). The specific indicators included: Mesor (mean activity level about which the circadian activity rhythm varies) p = 0.029, Hemicircadian Amplitude (twelve hour height of the cosine function above or below the mesor) p = 0.042, mean Diurnal Activity (counts per five-minute epoch from 0700 to 2300 hours - daytime) p = 0.012, and M10 (total activity of the 10 most active hours) p = 0.011. Sleep efficiency was also higher in the community group although the difference was not statistically significant (p = 0.115) These significant differences in cognitive function and activity occurred even though the congregate dwellers had more accessible environments (more ramps, elevators, automatic doors, few barriers) and more areas in which to socialize.

Table 4. Circadian Locomotor Activity of Participants

Variables	Community	Congregate	f	p
Mesor (average) Activity	609 ± 27	522 ± 11	4.67	0.029
Amplitude (Hemicircadian)	197 ± 75	139 ± 41	4.52	0.042
Mean Diurnal Activity	847 ± 40	715 ± 34	7.33	0.011
M10 (mean 10 most active hours)	11800± 450	10200 ± 390	7.12	0.012
Mean Sleep Efficiency	88.5± 3.4	81.3 ± 2.9	2.64	0.115

5. Conclusions and Suggestions for Future Work

This study characterized the elderly person's physical environment and related this characterization to their cognitive function and well-being. Two measures of the environmental complexity as well as its aesthetic appeal were determined. Both measures of environmental complexity (determined quantitatively from photographs of the participant's environment and qualitatively by VALs of the same photographs) were greater for the community group than the congregate housing group. The aesthetic appeal rating showed no difference between the two groups. Elderly persons living in environments of greater complexity displayed greater cognitive function and more robust circadian rhythms of locomotor activity. The emotional well-being measures showed no statistically significant difference. Thus, complexity is a different measure of than aesthetics. Similarly, cognitive function is a different measure than well-being. The correlation found between complexity and cognitive function is consistent with the hypothesis that a complex environment maintains cognitive function, however we note that this is a correlational rather than causational study. The lack of difference in emotional well-being indicates, counter to the hypothesis, that complexity does not correlate with emotional well-being. It is tempting to conclude that an emotionally comfortable existence can be found in simple unchallenging environments as well as complex ones. Thus, that challenge is not necessary to emotional comfort and that emotional comfort is not necessarily conducive to maintenance of cognitive function. The fundamental implication is that complexity is a different quality than aesthetics, and should be a major consideration guiding the design of environments, including housing for the elderly.

Because it was a preliminary study, the validity and reliability of the measures of complexity warrant replication and additional exploration. Generalizations of the findings are also limited by this study's small, convenience sample. Techniques to collect larger data sets are needed to use promising new methods to visualize patterns in human phenomena. The availability of a systematic measure of environmental complexity is an important complement to measures of physiologic time series, such as heart rate dynamics, which have been developed in recent years. Combining these two approaches holds promise for discovering patterns in human-environment relationships when sufficient data can be obtained to relate these phenomena.

Information in the environment challenges living things. The environments of elderly people should provide sufficient complexity of stimuli and information to challenge and thus exercise neurons in the aging brain as well as other tissues and organs. Complex, challenging and changing environments, that are within the elder's ability, but require effort, should stimulate the aging brain and body to maintain neurons, muscle fibers, and other tissues. Information theory indicates that when a recipient of a message has already received the message, and knows a message is being repeated, then no new information is being transmitted. When the system is at equilibrium, complexity disappears. Therapeutic environments and the caregivers working in them should utilize environmental patterns to stimulate all of the senses: auditory, visual, tactile, olfactory, and gustatory. Examples for fostering complexity of environmental patterns might include: the use of gardens and indoor plants; curving paths with interesting nooks; artwork in public and private places; furnishings of varied color, pattern and texture; varied foods; changing personalized and holiday decorations; books, magazines, newspapers, videos; and visits of family and friends. While such common sense recommendations extend beyond the results of this study, future scientific studies that investigate their relevance may increase the seriousness by which caregivers take these issues. The importance of these preliminary findings should be recognized. The consequences to the individual as well as to society of improving cognition and activity level of the elderly are significant. The implications for continued contribution, autonomy, and the reduction of costs anticipated for elder care justify further inquiry. While building effective care for the elderly is of universal importance, current and projected future demographic relevance has drawn increasing attention to these issues. Environmental complexity may be a powerful resource in our search for a high quality of life in old age. A specific approximate measure of the visual environment provides a means to examine the human experience of complexity in order to understand the effects of stimulation and sensory deprivation and the maintenance of cognitive function. Designing environments that are sufficiently complex to maintain or even restore a high level of mental and physical functioning may become an important part of plans designed to keep elders healthy.

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