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Viewing eye movements during reading through the lens of chaos theory: How reading is like the weather

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Do all readers read alike? Most educators would answer no. Even within a group of readers with similar proficiency levels there is variation and unpredictability in many aspects of the reading process. Differences can include the variety of ways readers approach the text, the types of oral reading miscues they make, the level of comprehension they demonstrate, the connections they make, and more. There is also intrareader variability in these aspects across texts and situations. A reader reading the same text at two different times would be unlikely to read in exactly the same way each time. Many literacy professionals might agree that no two reading acts are exactly the same; within the parameters of what is viewed as "reading" exist much inter- and intrareader variability and unpredictability. Few theoretical models of reading, however, emphasize this variability. In his analysis of contemporary models of reading, Tierney (1994) pointed out that while some theorists include variation and idiosyncrasy in models of reading, "their ramifications for ongoing and indefinite meaning-making are not embraced" (p. 1172). Instead, aspects of reading that are not predictable and do not fit neatly into a model or theory are typically disregarded or ignored. Such models "appear to offer a more segmented and straightforward depiction of the elements and their interrelationships than may exist" (Tierney, p. 1176). Robinson and Yaden (1993) offered a similar critique in terms of literacy research, questioning research that is based on data that assume linearity and a direct relationship between a particular variable and the desired outcome. They argued that "reductionist models that center on only one aspect of the reading process may in fact present an invalid picture of what is actually taking place during reading instruction" (p. 20). A perspective on

Viewing eye movements during reading through the lens of chaos theory: How reading is like the weather

THIS THEORETICAL article examines reading processes using chaos theory as an analogy. Three principles of chaos theory are identified and discussed, then related to reading processes as revealed through eye movement research. Used as an analogy, the chaos theory principle of sensitive dependence contributes to understanding the difficulty in predicting the nature of a reader's eye movement regressions, the principle of self-similarity is realized in the statistical similarity of a reader's eye movements at different levels of text, and the principle of nonlinearity is demonstrated through the intersection of eye movements and oral reading miscue analysis. When related to chaos theory in this way, reading can be described as a self-similar, nonlinear dynamical system sensitively dependent on reader and text characteristics throughout the reading process. Implications of viewing reading processes through a chaos theory perspective are discussed.

Consideración de los movimientos oculares durante la lectura a través del lente de la teoría del caos: En qué se parecen la lectura y el clima

ESTE ENSAYO teórico examina los procesos de lectura usando la teoría del caos como analogía. Se identifican y discuten tres principios de la teoría del caos y luego se los relaciona con los procesos de lectura tal como se revelan en las investigaciones sobre movimientos oculares. Usado como analogía, el principio de la dependencia sensitiva ayuda a comprender la dificultad para predecir la naturaleza de los movimientos oculares regresivos de un lector, el principio de la autosimilitud se realiza en la similitud estadística de los movimientos oculares de un lector en diferentes niveles del texto y el principio de la no linealidad se demuestra a través de la intersección de movimientos oculares y análisis de errores en lectura oral. Cuando se la relaciona con la teoría del caos de esta forma, la lectura puede describirse como un sistema dinámico autosimilar, no lineal, sensitivamente dependiente del lector y las características del texto a través del proceso de lectura. Se discuten las implicancias de la consideración de los procesos de lectura a la luz de la teoría del caos.

Betrachten von Augenbewegungen beim Lesen durch die Optik der Chaos-Theorie: Wie das Lesen dem Wetter gleicht

DIESE THEORETISCHE Abhandlung untersucht Leseprozesse unter Nutzung der Chaos-Theorie als eine Analogie. Drei Prinzipien der Chaos-Theorie werden identifiziert und diskutiert, so dann zu Leseprozessen in Beziehung gesetzt, wie sie durch die Erforschung der Augenbewegung ermittelt wurden. Angewandt als eine Analogie, trägt das Chaos-Theorie-Prinzip der sensitiven Dependenz zum Verständnis der Schwierigkeit in der Voraussage der Beschaffenheit von Augenbewegungsregressionen eines Lesers bei, mithin wird das Prinzip des Selbstvergleichs im statistischen Vergleich der Augenbewegungen eines Lesers bei unterschiedlichen Einstufungen des Textes realisiert, und ferner ist das Prinzip der Nichtlinearität durch den Schnittpunkt von Augenbewegungen und der Analyse mündlicher Fehlhinweise dargestellt. Wird es dann in dieser Weise auf die Chaos-Theorie bezogen, so kann das Lesen als ein selbstvergleichendes, nichtlineares, dynamisches System beschrieben werden, dabei durchaus sensitiv abhängig von Leser- und Textcharakteristiken während des gesamten Leseprozesses. Auswirkungen über die Beurteilung von Leseprozessen aus der Perspektive der Chaos-Theorie werden diskutiert.

カオス理論のレンズを通して行うリーディング中の目の動きの考察：リーディングと天気の類似

この理論的論文は、カオス理論をアナロジーとして用いて、リーディングの過程を検討する。カオス理論の３つの法則を挙げて議論し、目の動きの研究を通じて明かになったリーディング過程に関連付ける。アナロジーとして用いられると、カオス理論の敏感な依存の法則は、読み手の目の動きの退行の性質を予測する難しさを理解することに貢献し、自己類似性の法則は、異なるレベルのテキストでの読み手の目の動きの統計上の類似において認知され、非線形性の法則は、目の動きと口頭による読みのミスキュー分析との交点を通じて明白にされる。このようにカオス理論に結び付けられると、リーディングは、読みの過程の初めから終わりまで読み手とテキストの特徴に敏感に依存した自己類似的、非線形的で動的なシステムと言うことができる。カオス理論の視点からリーディング過程を見ることの示唆を述べる。

Considérer les mouvements des yeux pendant la lecture à l'aide des lunettes de la théorie du chaos : en quoi la lecture est-elle comme le temps

CET ESSAI théorique examine les processus de lecture par analogie avec la théorie du chaos. On a identifié et discuté trois principes de la théorie du chaos, puis fait la relation avec les processus de la lecture tels qu'on peut les saisir au moyen des mouvements oculaires. En tant qu'analogie, le principe de dépendance sensible de la théorie du chaos permet de comprendre les difficultés qu'il y a à prédire la nature des mouvements de régression de l'œil du lecteur, le principe d'auto-similarité est réalisé par la similarité statistique des mouvements oculaires du lecteur à différents niveaux du texte, et le principe de non-linéarité est démontré au moyen de l'intersection entre mouvements oculaires et analyse des erreurs en lecture orale. Reliée de la sorte à la théorie du chaos, on peut décrire la lecture comme un système dynamique auto-similaire, non linéaire dépendant sensiblement des caractéristiques du lecteur et du texte au cours du processus de lecture. On discute des implications du fait de considérer les processus de lecture selon la perspective de la théorie du chaos.

Движения глаз при чтении сквозь призму теории хаоса: в чем сходство чтения с погодой

Данное теоретическое эссе исследует процессы чтения, используя в качестве аналогии теорию хаоса. Сформулированы и рассмотрены три принципа теории хаоса, установлена их связь с процессом чтения и непосредственно с движениями глаз при чтении. Принцип чувствительности и изменяемости (невозможности точно предсказать состояние системы) позволяет понять, почему трудно предсказать характер рекурсивных движений глаза читателя; принцип самоподобия ("наследственной предсказуемости") проявляется в статистически устойчивом сходстве движений глаз одного читателя при чтении текстов различного уровня; принцип нелинейной динамики – в корреляции движений глаз и анализе неточностей при чтении. В соответствии с теорией хаоса, чтение может быть описано как самоподобная, нелинейная динамическая система, сенсорно зависимая от читателя и свойств текста в течение всего процесса чтения. Представлены выводы, следующие из рассмотрения процесса чтения с точки зрения теории хаоса.

reading that takes such unpredictability and variability into account and allows educators and researchers to view and discuss reading processes in their entirety would be valuable. In this article, I argue that chaos theory can provide that perspective.

In physics, chaos theory is an approach valued in part because of its ability to model complex, seemingly random dynamic processes. It describes systems in which variations in processes that were previously thought to be simply mistakes or unimportant noise have been shown to be integral to that system, and it has helped scientists understand and explain unpredictability and irregular behavior. Chaos has caused a paradigm shift and a "transformation in a way of thinking" (Gleick, 1987, p. 37) in physics. By linking reading processes to chaos theory, we may find similar, fresh ways to look at, think about, and discuss reading processes. More specifically, there may be direct pedagogical and research implications of viewing reading through a chaos theory lens. As an example of the latter, chaos scientists Crutchfield, Farmer, Packard, and Shaw (1986) noted that "chaos brings a new challenge to the reductionist view that a system can be understood by breaking it down and studying each piece" (p. 56). Related to reading processes, that aspect of chaos theory's challenge to reductionism can inform critiques of reductionist models of reading and potentially affect literacy research in general, as Robinson and Yaden (1993) have discussed.

Making a connection between chaos theory and reading may raise some eyebrows. Chaos theory applies to physical science, where outcomes are tangible and demonstrably measurable. In contrast, one can't touch or weigh a cognitive process like reading. However, I propose here that chaos theory can be a useful analogy for viewing reading processes. Analogies play an important role in scientific discovery (Holyoak & Thagard, 1997) and are powerful forces in conceptual change (Gentner & Holyoak, 1997). The purpose of constructing the analogy in this article is not to offer evidence-based conclusions but to engage the reader in considering reading processes from a different vantage point. Like Duke (1994), I believe that patterns of theory and research generated in physical science can be useful in generating conceptualizations and hypotheses in cognitive areas of human development.

While most analogies adhere to the formula of constructing an analogy around a concrete reference in order to illustrate properties of a target reference, in this article I follow Kurtz, Miao, and Gentner's (2001) work in comparing principal aspects of two systems in order to engender deeper comprehension of one. This type of analogy is a "means of increasing sophisticated understanding and representation through a comparison process according to which key components of meaning are made salient, roles are made explicit, and relations are made evident" (Kurtz et al., p. 420). As such, in this article, key principles of chaos theory and relevant aspects of reading processes are related to each other.

While cognizant that no single methodology will completely cover all conceptualizations of the process of reading, to represent the reading processes side of the analogy I use eye movement research. Ecological validity is one reason for this choice. Eye movements have been used as a measure of online processing, as opposed to inferring processing after the fact (as in a comprehension test) or through an additional task, such as think-alouds or decision making (Rayner & Pollatsek, 1987). When reading, the eyes make a series of stops, called fixations, in order to provide the brain with usable graphic data. During a fixation, the eye provides a very small amount of in-focus information to the reader (Just & Carpenter, 1987; Rayner & Pollatsek, 1989). In order to literally see a word in focus, the reader usually must directly fixate that word, but note that syntactic and semantic context allows readers to skip words, and this is a regular occurrence (Ehrlich & Rayner, 1981; Rayner, 1998).

There is a strong link between where a reader fixates and moment-by-moment attention (Chaffin, Morris, & Seely, 2001) and "by examining where a reader pauses, it is possible to learn about the comprehension processes themselves" (Just & Carpenter, 1980, p. 329). This is not to be interpreted as revealing what the reader is thinking, but rather that

> The time that a reader spends on various parts of a text and the places where he fixates or rereads the text are excellent indices of the ongoing psychological processes. The time a reader spends on a word or a phrase can indicate when a process occurs and how its duration is influenced by characteristics of the text, the reader, and the task. (Just & Carpenter, 1987, p. 5)

Particularly when combined with another comprehension measure, as is done here with miscue analysis recording and procedures, eye movements can provide a powerful window into the reading process (Paulson & Freeman, 2003). Eye movement technology has progressed to the point where it is virtually unobtrusive to the reader and measures exactly where and when the reader looks at which letter of which word in the text. This provides a spatial and temporal map of the reading process and is effective as a representation of reading processes.

This chaos theory/reading processes analogy is represented on the chaos theory side by *sensitive dependence, fractal self-similarity*, and *nonlinearity*, three principles that are part of most chaos theory research and descriptions (e.g., Gleick, 1987; Lorenz, 1993). Below, those principles are introduced, and in subsequent sections, each of those principal aspects of chaos theory is then further described and related to reading processes as represented by eye movements. Those sections are followed by a general discussion section that integrates the different foci in this essay.

Introduction to chaos theory

In the early 1960s, meteorologist Edward Lorenz set out to determine why accurately predicting weather patterns was seemingly impossible. Building a computer model of the earth's weather, Lorenz used nonlinear differential equations to model mathematically generated visuals of weather patterns. Gleick (1987) described how Lorenz stopped one of his sequences in midcourse and then, instead of starting the same sequence over from the beginning, typed in the mathematical values from where he had left off. This would, he reasoned, cause the sequence to end up at exactly the same place as a previous sequence that used the same starting values. However, the sequence varied slightly during each iteration, until it was wildly different than the original. After some investigation, Lorenz found that the midpoint values he had used to restart the sequence, which were limited to three decimal places on the printout he had, were actually stored in the computer up to six decimal places. Thus, when he restarted his sequence with the three-digit value, he was, in effect, starting the sequence from a slightly different place, which produced much different results. This small difference in values was amplified and built on until the end result was far from the expected result. It was Lorenz's (2000) work that stimulated the description of the "butterfly effect"; the famous question Lorenz posed was whether a butterfly flapping its wings in Brazil can influence tornado patterns in Texas months later (Lorenz, 2000). The technical term for the butterfly effect is *sensitive dependence on initial conditions*, and Lorenz's (1963) early work with weather patterns is generally considered the birth of chaos theory (Gleick, 1987).

If chaos is the process, the product is best expressed as a self-similar fractal (Koehler, 1995). Coined by Mandelbrot (1983) to describe non–Euclidian shapes found in nature, fractals describe objects that may seem irregular in shape but actually have an iterative, self-similar design at many different scales. A head of broccoli is a good example in that any one of the branches that make up the head retains its similarity to the head as a whole, yet each is unique in some respects. Fractals owe their unique shapes and descriptions to the type of attractors found in chaotic systems. An attractor is a representation of influences that move the system toward a steady state; "roughly speaking, an attractor is what the behavior of a system settles down to, or is attracted to" (Crutchfield et al., 1986, p. 50).

Chaos theory describes systems that are rule governed but where the exact outcomes are almost impossible to predict. That is, they do not progress according to a linear process where a small change will produce a small and easily measured outcome. Instead they are nonlinear, and this nonlinearity is a necessary part of chaos (Lorenz, 1993).

A complete description of chaos theory would entail volumes; however, for the purposes of this article chaos is considered a nonlinear process that is sensitively dependent on initial conditions and exhibits self-similar fractal relationships. These three chaos theory principles of sensitive dependence, fractal self-similarity, and nonlinearity are used to analogically link chaos theory and reading processes as represented by eye movements. The first of these principles, sensitive dependence, is related to reading processes in the next section.

Sensitive dependence on initial conditions

Sensitive dependence is the idea that small fluctuations or differences in a system will not simply level out and be inconsequential, but rather will be multiplied and can change the course and makeup of that system dramatically. Despite the term *initial conditions*, which implies that only the beginning state is important, chaotic systems are sensitively dependent on conditions that occur throughout the time course of the system (Lorenz, 1993). That is, it is not just where a system begins but what it encounters throughout its existence that shapes its course. This is important as it relates to weather, because the idea of a butterfly flapping its wings being the beginning of a weather system is a false one; there are no sharply defined beginnings or endings to the continuous system that is weather.

And like the weather, reading doesn't have a clear beginning or ending. While there can be a physical text with a first word and a last word, read-

ing also involves a reader. Theory and research by Rosenblatt (1978, 1994), Whaley (1981), and Zwaan (1994), among others, have demonstrated convincingly that the stance a reader holds greatly affects what the reader experiences, comprehends, and remembers as a result of reading a particular text. Schema theory (e.g., Anderson, 1994; Bartlett, 1932) further informs the idea that a reader's background experiences and expectations are crucial factors that affect comprehension. As Anders and Guzzetti (1996) pointed out, "prior knowledge determines how we comprehend...[and] if we comprehend at all" (p. 12). That is, where readers end up in terms of comprehension depends in part on their initial schemata, and there is ample research demonstrating that appropriate schemata have direct effects on text comprehension (e.g., Anderson; Faris & Smeltzer, 1997; Steffensen, Joag-Dev, & Anderson, 1979). In the sense of a starting point, the difference in individual readers' schema is akin to differences in initial conditions in the weather example above.

However, in terms of the weather example, saying that differences in readers' prior knowledge determines whether or not they will understand the text is like saying that differences in relative humidity determine whether or not the weather will feel muggy. While partially true, it does not take into account dozens of other atmospheric changes that can be affected by initial conditions. Dew point, barometric pressure, temperature, wind velocity, and more can and should be measured when explaining how the weather became muggy. In the same way, describing how reading is sensitive to initial conditions requires a tool that can show microscopic patterns as well as macroscopic ones. For this reason, readers' eye movements are used to describe reading processes in this article, because measuring microprocesses like eye movements can accurately display subtle differences between and within readers (Rayner, Raney, & Pollatsek, 1995).

Regressive eye movements and sensitive dependence

In a rule-governed, nonrandom system, we should be able to predict observable phenomena with considerable accuracy. Newtonian laws of motion and gravity, for example, enable accurate prediction of the appearances of Halley's comet as well as oceanic tides many years into the future. In contrast, a rule-governed system that is also chaotic is difficult to predict with any accuracy (e.g., the weather). Eye movements are rule governed because they are not random; they reflect reading processes and how the reader navigates the text. Regressions—eye movements that go "backward" in the text—are the focus in this section. Around 10–15% of a reader's fixations are regressions (Rayner & Sereno, 1994), and readers make a regression about once every two seconds (Rayner & Pollatsek, 1989). Regressions are a good indicator that the reader is actively dealing with problem areas in the text, such as syntactic or semantic complexities or word identification problems (Vitu & McConkie, 2000). If regressions are able to be explained and predicted with a great deal of accuracy, chaos theory would seem not to make a very good analogy for reading. On the other hand, if regressions are clearly caused by something—and are not random—yet they can't be predicted accurately, the sensitive dependence principle of chaos theory may provide a useful analogy for their existence.

Causes of regressions

Regressions have a multitude of causes that includes text variables such as awkward syntax or low-frequency words (Engbert, Longtin, & Kliegl, 2002), reader confusion (Bouma & Devoogd, 1974; Buswell, 1920; Just & Carpenter, 1980; Shebilske & Fisher, 1983), disconfirmation of an interpretation (Frazier & Rayner, 1982), difficulties or failures in word identification, or incomplete lexical processing (Engbert et al., 2002; Rayner, 1998; Vitu & McConkie, 2000). In addition, reduced visual acuity in the periphery (Brysbaert, Vitu, & Schroyens, 1996) can cause a regression, as well as a reader overshooting or undershooting the beginning of the line (Rayner & Pollatsek, 1987), and regressions are more likely to happen if the word that is subsequently regressed to was skipped when the reader first read that portion of the text, especially if that word is low frequency (Brysbaert et al., 1996; Inhoff & Rayner, 1986). These variables can also often be correlated with higher order processes and global reading difficulty (Rayner & Pollatsek, 1989; Reichle, Pollatsek, Fisher, & Rayner, 1998) in explaining the presence of regressions.

With all these potential causes of a regression, is there one that seems primary? Not really. Even in Vitu and McConkie's (2000) study, which demonstrates support for word identification being an important variable in eye movement regressions, the researchers included a caveat in their conclusion. While some of their predictions are supported, others are not. And even for the support for their hypothesis that they did find, they noted, "the word identification explanation is not the only possible ex-

planation for several of the results that have been reported here" (p. 324). This is an indication that it is very difficult to pinpoint one overriding reason explaining why readers regress to parts of the text previously viewed, and regressions probably happen for a combination of the above reasons. Knowing exactly which causal factor will be prominent at which time appears to be dependent on unpredictable text–reader interactions.

So it is difficult to explain why regressions happen, in general; it stands to reason it is even more difficult to predict the nature of a regression. Here are a few of the dozens of spatial questions about regressions: From which word will a regression be launched? To which word will the regression be aimed? Which part of the word will be regressed to? Are all regressive sequences similar in pattern? To emphasize the possible differences in regressions, example eye movement records are examined below.

Regressions have an infinite number of forms

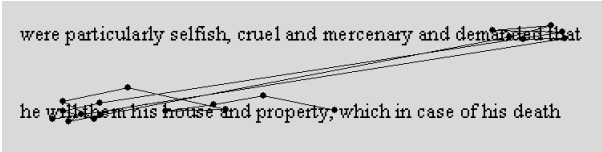
One of the texts readers read in the eye tracking clinic at the University of Cincinnati, Ohio, USA, is a short story containing a sentence that usually causes readers to employ some sort of correction strategy when they first read it. This is the sentence:

> Unfortunately, his own parents were particularly selfish, cruel and mercenary and demanded that he will them his house and property, which in case of his death would have gone to his wife.

The author's use of *will* in the sentence as a primary verb is not as common as its use as a modal verb, and readers tend to expect the latter. After reaching parts of the sentence subsequent to *will*, readers usually realize that their initial prediction of the verb's syntactic and semantic properties was disconfirmed, and they will typically use some sort of strategy to correct that interpretation. Many times this correction is realized through a sequence of eye movement regressions—so, in that sense, it is possible to predict where in a given text a reader may make a regression.

However, such a prediction is far too general and doesn't reveal much about the process beyond that readers make regressions in syntactically awkward text. Of the 10 most recent readers to read this story (university undergraduates who volunteered for an eye tracking study and read this story as one of a series of practice texts), 2 did not make a regression in the "demanded that he will them his house" area at all. The other 8 displayed a variety of regressive strategies. An excerpt from the eye movement record of one of these is illustrated in Figure 1.

FIGURE 1
READER'S REGRESSION ON *WILL* EXAMPLE



In Figure 1, the reader fixated forward on *demanded*, *that*, *will*, and *them*, then regressed to *will*, went forward to *them*, regressed back up to the previous line to fixate *demanded* and *that*, proceeded forward to *them*, regressed back to *will*, and then generally proceeded forward. Other readers, while also making regressions in this area, exhibited different patterns, as described in Table 1.

The variability among just these 10 readers is considerable, and it should be noted that multiple fixations on words, as well as fixation durations, were ignored for the sake of clarity in the simplified descriptions given here. Even at a relatively broad level of analysis concerned only with which word was subsequently fixated (as opposed to which region of a specific word, or other more detailed prediction), there is no repetition among these readers. It seems apparent from the sheer number and type of regressions available even in one sentence of one text that simply deciding that text difficulty causes regressions provides no real insight to the reading process. Predicting where and when these regressions will happen is even more difficult, as the difference between readers in the illustration given shows. And in addition to differences in eye movements between readers, in terms of regression frequency, there is considerable within reader variability as well (Rayner, 1997).

Eye movement regressions are sensitive to conditions that occur throughout the reader's interaction with the text. Globally, we know readers will make a certain amount of regressions; locally, however, it is not possible to reliably predict exactly where and how a reader will regress. Those decisions are made by the reader on an as-needed basis in response to elements of the reading process that occur throughout the reading.

TABLE 1
TEN READERS' REGRESSION PATTERNS

Reader	Regression pattern
1	No regression
2	(Displayed in Figure 1)
3	Fixated on *will*, then *his*, regressed to *them*, progressed normally after that.
4	Fixated several times on *that* and *them*, regressed back to *that*, then forward to *he*, *his*, and *and*, regressed to *that*, then forward.
5	Fixated forward on *he* and *his*, then regressed back to *he* before continuing forward to *his*, *house*, *and*, *property*, then regressed back to *house* before continuing.
6	Fixated forward on *will* and *his* before regressing to *them* and *will*. He then fixated forward on *his* and *house* before regressing to *he* and *that*, then forward to *will*, *his*, and *property*.
7	No regression
8	Fixated forward on *demanded*, *that*, *he*, and *his*, then regressed back to *them*, regressed again to *will*, forward to *house*, back to *his*, back to *will*, forward to *his*, *house*, *and*, and *property*, then back to *which*, and finally forward to *property*.
9	Fixated on *demanded*, *that*, and *will*, then regressed to *that*, fixated forward on *them*, back to *will* and forward to *them*, *his*, and *and*, regressed back to *demanded*, and forward to *property*.
10	Fixated on *demanded*, *that*, *he*, and *his* before regressing to *them* and backing up to the previous line on *that*, after which he refixated *his* and then progressed forward.

Regressions display characteristics of sensitive dependence

The placement and duration of an eye fixation affect when and where subsequent eye fixations will take place. For example, a skipped word is more likely to be regressed to than a nonskipped word (Vitu, McConkie, & Zola, 1998). But while it may be possible to state that a regression is likely to happen after a skipped word, that does not move us much closer to predicting the exact location and nature of the regression, because skipped words themselves are difficult to forecast from reader to reader. In order to know exactly where a reader will regress to and from, we would need an unimaginable amount of information about the reader's background knowledge and schema as it applies to the text in question, in addition to millisecond-by-millisecond information relating to how the reader will process each letter, word, phrase, and so on. This impossible amount of information needed for exact predictions is typical of chaotic systems. Kellert (1993) stated, "this, then, is the limitation posed by sensitive dependence: *chaotic systems require impossible accuracy for useful prediction tasks*" [italics in original] (p. 35).

Like a chaotic system, the system that is reading is subject to moment-by-moment choices and interpretations by the reader that affect the reading process itself. In Table 1, readers 1 and 7 made no regressions in the "that he will them" area. Though not conclusive, this is one indication that this area presented no special comprehension difficulties to those readers. The other readers' parsing of the sentence may have each been disconfirmed, which set off a series of regressive eye movements, all of which were realized in different ways in different readers. In chaos theory, when each subsequent action builds the previous one into it, it is termed *iterative*. Hayles (1990) explained iteration as being "analogous to beginning at a certain place and doing a dance step; then starting from the new location each time, doing the dance step again and again" (p. 153). In this sense, regressions are clearly iterative, as each fixation determines in part where the next one needs to go. Eye movements in general are iterative as well, which helps explain their self-similarity at many scales—the next principle to be discussed.

Self-similarity: Fractal relationships

One way to measure the nonlinear dynamical process is to examine its fractal properties. A fractal is manifested by "repetition of detail at descending scales" (Briggs & Peat, 1989, p. 90), revealing greater detail at greater magnifications while still retaining similarity to the whole object. Like the broccoli example given earlier, a tree is a visual example of self-similarity at many different magnifications. Seen at a distance, it has a structure that is replicated when examining a single limb with its own smaller limbs branching off, and it is replicated again when the veins in a leaf of that tree are seen at close range.

Mandelbrot (1967) provided another example of self-similarity in an article title with a now-famous question meant to illustrate a central idea in the study of fractals: "How long is the coast of Britain?" Mandelbrot's article demonstrates that different tools will give different measurements of an uneven surface, such as a coastline. If we use a yardstick, we will produce one number, but the yardstick will pass over—and thus not measure—twists and turns smaller than a yard. If we use a ruler, which can measure more accurately some of the twists and turns that the yardstick skipped, we'll get a longer measurement, because more length has been added to the perimeter due to our measuring tool's smaller scale. Similarly, if we decide to measure with even more accuracy, we could use a tool that proceeds in inch increments, which will provide a more accurate measurement than either the yardstick or the ruler. This is the fractal idea of greater detail at greater magnification. Kellert (1993) explained,

> A jagged coastline provides a useful example of a fractal-like object. Observed from afar, the coastline reveals some peninsulas and bays; on closer examination, smaller juts and coves are seen, and these again reveal jagged borders when surveyed more closely. (pp. 15–16)

The tree and coastline examples have obvious visual fractal attributes. Other fractal relationships are better expressed in terms of their statistical self-similarity (Lorenz, 1993). For example, Mandelbrot (1963) looked at the rise and fall of cotton prices on the New York Stock Exchange over a 60-year period and found that, regardless of the scale examined, there were similarities in price fluctuation. Gleick (1987) explained that "the sequence of changes was independent of scale" and that "analyzed Mandelbrot's way, the degree of variation had remained constant over a tumultuous sixty-year period that saw two World Wars and a depression" (p. 86). In the stock exchange example, self-similarity is expressed through similar irregular patterns of variation at the day, month, year, and decade scales of cotton price changes.

Self-similarity in reading

The next step in the construction of this chaos analogy is to look for self-similarity in reading. At greater magnification, will we find both greater detail and self-similarity of eye movements? Although there is not yet a large body of empirical evidence that eye movements during reading demonstrate fractal qualities, some research does exist (e.g., Holden, 2002; Schmeisser, McDonough, Bond, Hislop, & Epstein, 2001). For example, Schmeisser et al. (2001) used analyses such as the power spectral density, delay maps, and correlation dimension when they examined the eye movements of readers of differing skill levels. While their work was preliminary, they concluded that "the underlying mechanism for eye movement might be effectively modeled by a chaotic, nonlinear, dynamical system possessing a strange attractor with a noninteger dimension" (p. 812). The goal of this article is not to replicate such empirical evidence of the fractal qualities of eye movements during reading but instead to construct an analogy. Descriptive charts designed to illustrate the self-similarity inherent in eye movements during reading are used here; aspects of the figures follow Flurkey's (1997) innovative depictions of patterns in oral reading fluency.

To explore self-similarity in reading, one reader's reading of a short story (1,383 words) is examined at different scales, such as text, page, paragraph, sentence, and so on. Proceeding from the page scale to the paragraph scale is analogous to holding the text up to a magnifying glass, with the purpose of that magnification being a comparison of the same eye movement measure as seen at different levels of magnification. For example, if there is a relatively stable rate of word fixation across pages, does that stable rate of word fixation also apply when we look through the magnifying glass at paragraphs and sentences? Or if there is a variable rate of word fixation across pages, will we find similar variation at different magnifications? These questions are investigated through the exploration of three widely used eye movement measures examined at different scale levels.

Three measures of eye movements: Words fixated, fixation duration, and saccade length

Because the three eye movement measures of words fixated, fixation duration, and saccade length all represent responses readers make to the text when reading (Rayner, Raney, & Pollatsek, 1995), they are each briefly examined below in terms of their self-similarity at different scale levels. At issue is whether variation in these measures, or lack thereof, is replicated from level to level.

Self-similarity in percentages of words fixated

Although intuitively it may seem as though we look at every word while we read, eye movement re-

FIGURE 2
FIXATION PERCENTAGE BY PAGE

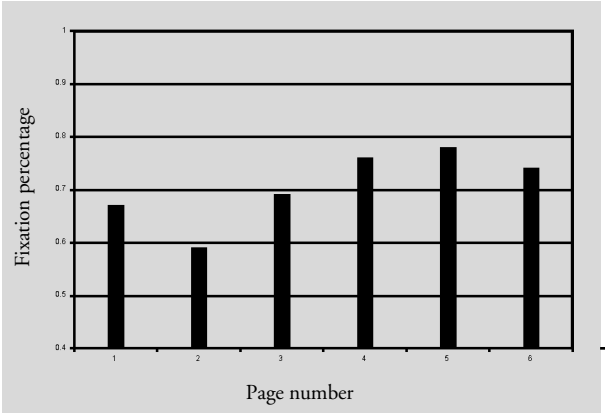
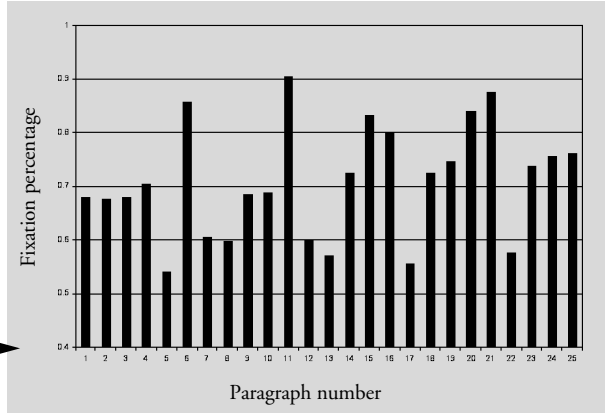
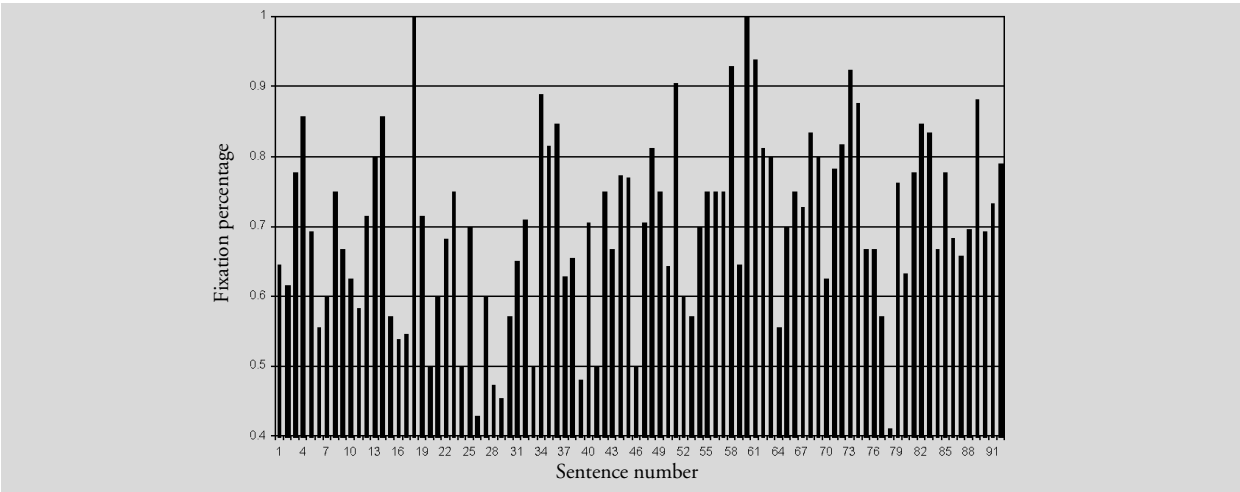


FIGURE 3
FIXATION PERCENTAGE BY PARAGRAPH



MAGNIFICATION

FIGURE 4
FIXATION PERCENTAGE BY SENTENCE



search has shown for more than a century that readers fixate in the neighborhood of two thirds or three quarters of the words in a text, and fixation percentages can range from 50–80% (see Buswell, 1922; Fisher & Shebilske, 1985; Huey, 1908/1968; Just & Carpenter, 1987; Paulson, 2002; Paulson & Goodman, 1999; Rayner, 1997). The reasons words can be skipped are various, with context and predictability of the skipped word assuming a significant role (Ehrlich & Rayner, 1981; Fisher & Shebilske, 1985; McClelland & O'Regan, 1981; Paulson & Freeman, 2003; Rayner, 1997; Rayner & Well, 1996). Certain types of words are fixated more frequently than others; for example, content words are fixated at a higher rate than are function words (Carpenter & Just, 1983). As is the case with regressions, where the eye fixates is a reasonably good indication of what the reader is attending to from moment to moment. This section examines self-similarity in the amount of words fixated. One reader fixated 70% of the words overall in the six-page text, and Figures 2, 3, and 4 show the percentages of words he fixated at the page, paragraph, and sentence levels.

Note that, like the coastline example discussed previously, greater magnification of the text results in greater detail. The irregular pattern of the *page* scale of Figure 2 is replicated in the *paragraph* scale of Figure 3, and again in the *sentence* scale of Figure 4, each time with finer detail. This similarity extends at every level from the page down to at least the clause level. Figure 5 excerpts parts of Figures 2–4 (and adds the *clause* scale of the text) to illustrate how

these three charts (and the ones that follow) can be thought of as showing different magnifications of an eye movement measurement. Figure 5 first shows the variability in words fixated on the page level, then focuses on one of those pages (page 3) to show the variability of the words fixated in the three paragraphs (paragraphs 8–10) of that page, then focuses on one of those paragraphs (paragraph 9) to show the word fixation variability in the sentences (sentences 37–41) that make up that paragraph, then focuses on one of those sentences (sentence 40) to show the word fixation variability in the clauses that make up that sentence.

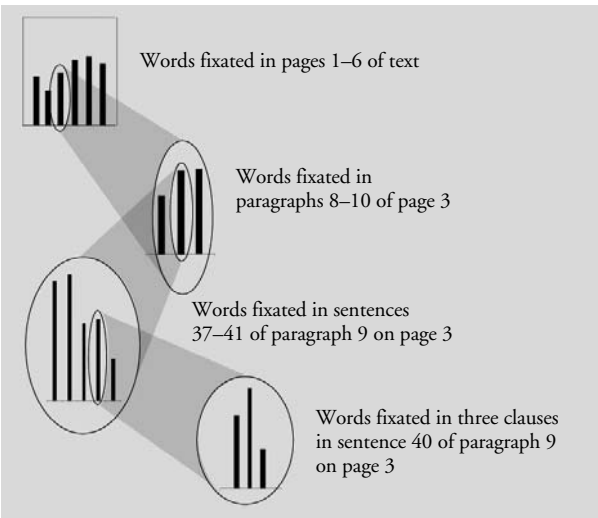
In essence, each chart excerpt is a magnification of the one before it, a look at percentages of words fixated on different scales. Imagine this as the chart form of a coastline, as described earlier, where every magnification provides greater detail yet still resembles the whole. There is no regular pattern of the amount of words fixated to which the system settles down. Instead of becoming a steady state at some scale, the pattern of word fixation remains variable; the norm is a changing rate of fixation percentage.

Self-similarity in fixation duration

The amount of time a reader spends on a particular word reflects the familiarity and frequency of the word and the extent to which it makes sense to the reader in the context in which it is found (Rayner & Well, 1996). That is, fixation duration reflects, among other things, predictability and contextual constraints of the text (Reichle et al., 1998). Shorter fixations are associated with words highly constrained by the context—predictable words—and longer fixations indicate parts of the text where the reader needed more processing time (Rayner & Pollatsek, 1989). Throughout the text, the differences in fixation duration from fixation to fixation illustrate variability in how the reader responds to the text. In Figures 6–8, the duration of fixations made by the same reader who provided the record above are shown in paragraph, sentence, and individual fixation scales.

Figures 6, 7, and 8 display durations of the reader's fixations and show a similar up-and-down pattern at different scales. Figure 6 shows average fixation durations at the paragraph level, Figure 7 shows average fixation durations at the sentence scale, and Figure 8 displays fixation durations on the level of individual fixations. As with the percentages of words fixated, the durations of fixations do not settle down into a fixed state but rather establish a pattern of fluctuation at different scale levels. This statistical self-similarity is an attribute present in fractals.

FIGURE 5
NESTING SEQUENCE OF WORD FIXATION CHART EXCERPTS



Self-similarity in saccade length

Like the location and duration of eye movements, saccade length is a measure that reflects reading processes (Rayner & Pollatsek, 1987). A saccade is the ballistic movement between two fixations, and the saccade length measures the distance between fixations. A series of short saccades indicates fixations that are close together, while longer saccades indicate fixations that are farther apart. A reading typified by many skipped words, for example, will also be typified in general by longer saccades. Shorter saccades can be found in intraword fixations, as well as in fixations from one word to the word immediately adjacent to it.

While saccade length alone cannot assess the level of reading comprehension, there are associations that can be made when saccade length is combined with other eye movement measures. Typically, shorter saccades are associated with more tentative reading that can be found on a difficult text, where the fixations are closer together. Likewise, longer saccades are associated with more confident reading in which the reader makes fewer fixations that are spaced farther apart (Rayner & Pollatsek, 1987). Figures 9–11 display the reader's average saccade length in degree of visual angle at the paragraph, sentence, and individual saccade scales. Return sweeps—saccades from the end of one line to the beginning of the next—have been removed since they

FIGURE 6
AVERAGE FIXATION DURATION BY PARAGRAPH

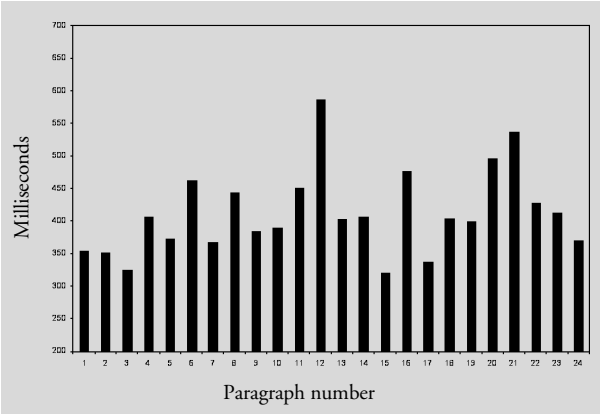
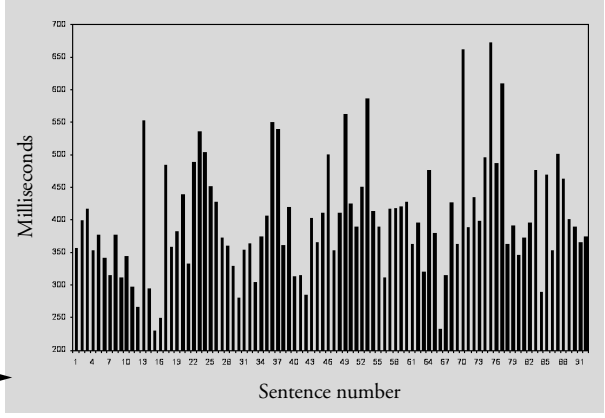
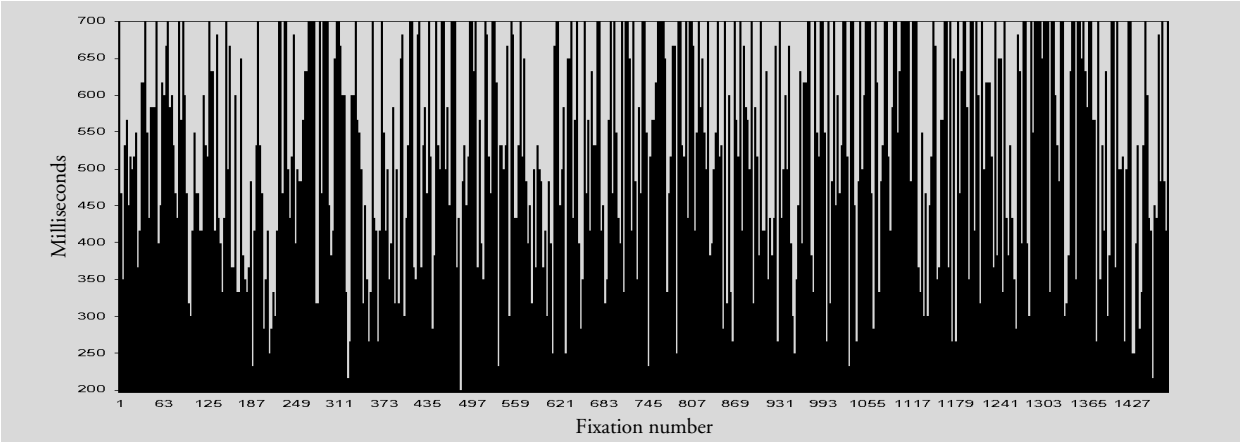


FIGURE 7
AVERAGE FIXATION DURATION BY SENTENCE



MAGNIFICATION

FIGURE 8
FIXATION DURATION BY INDIVIDUAL FIXATION



are a function of how many lines are in a sentence or paragraph, not a reader's response to the text.

The familiar erratic pattern is again present at the paragraph, sentence, and individual saccade levels. With each successive magnification, greater detail is shown, but the up-and-down pattern is always present. Like the percentage of words fixated and fixation duration, saccade length patterns show fractal-like attributes of self-similarity at several scale levels.

Eye movements display characteristics of self-similarity

Mandelbrot's (1999) example of fractal self-similarity in the statistical variation in stock market prices lends itself to comparison with the self-similarity of word fixation percentages, fixation durations, and saccade length across scale levels. Like stock market price fluctuations over the course of a year, a month, and a day, eye movement variability examined on the scale of a page resembles variability on the scale of a paragraph, which, in turn, resembles that of a sentence, and so on. Mandelbrot explained that "volatility—far from a static entity to be ignored or easily compensated for—is at the very heart of what goes on in financial markets" (p. 73) and that "movements of a stock or currency all look alike when a market chart is enlarged or reduced so that it fits the same time and price scale.... This quality defines the charts as fractal curves" (p. 71). There is a sameness to each of the scale levels within the fixation percentage, fixation duration, and saccade

FIGURE 9
AVERAGE SACCADE LENGTH BY PARAGRAPH

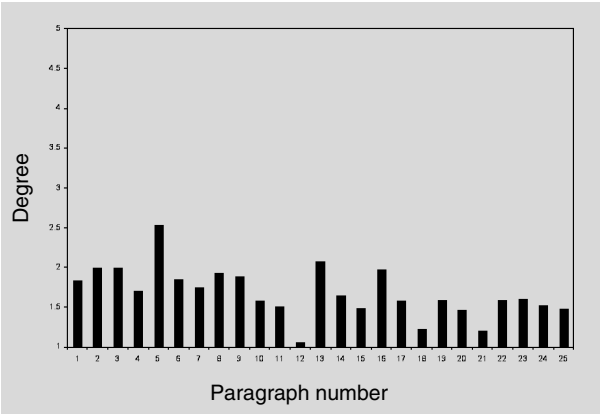
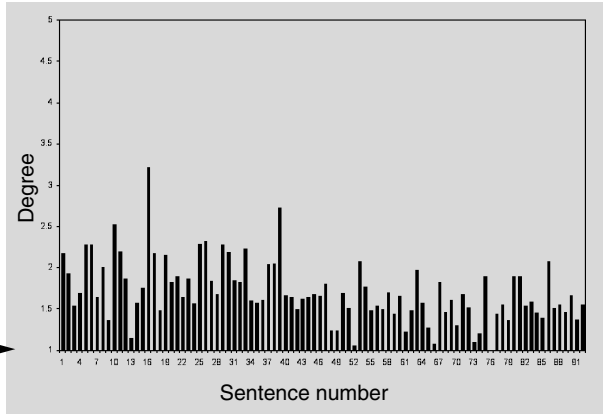
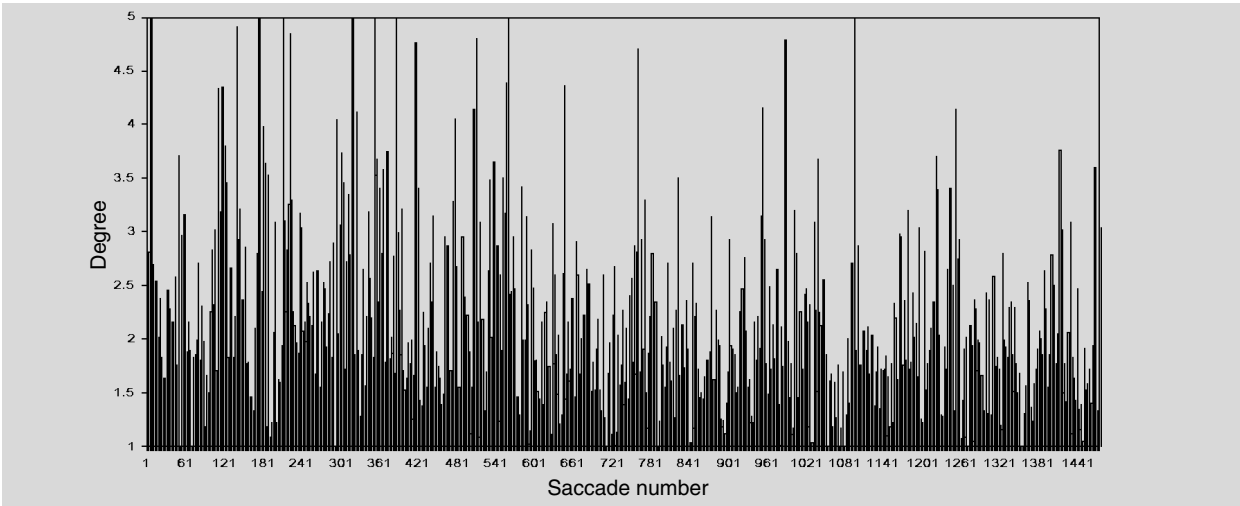


FIGURE 10
AVERAGE SACCADE LENGTH BY SENTENCE



MAGNIFICATION

FIGURE 11
SACCADE LENGTH BY INDIVIDUAL SACCADE



length charts. Like the fractal nature of the stock market, looking at these aspects of a reader's eye movements in this way assists in the construction of the chaos theory analogy of reading.

While fracticality is usually used to describe physical constructs, it is not without precedent that fractal properties have been applied to human characteristics. Torre (1995) explained that "thinking and problem solving are fractal in nature because the structured irregularity of their processes and interactions exhibit statistically self-similar structure on all scales" (p. 194). Historically, viewing reading as a cognitive, reasoning activity has a well-established foundation (e.g., Thorndike, 1917), so the links between thinking and problem solving, as Torre described, and reading can be made aptly. Fracticality may apply to general language processes as well; Larsen-Freeman (1997) constructed a compelling analogy for language exhibiting fractal qualities by relating language to Zipf's power law connecting word rank and word frequency. Her example demonstrates "the self-similarity of scale in language that is intrinsic to fractals in the natural world. The pattern that exists at one level of scale holds for other levels and for the whole system" (p. 150).

The evidence from eye movement research and examples of word skipping, fixation duration, and saccade length presented in this section suggest that eye movements are iterative and are analogous to the fractal property of self-similarity at different scales.

One reason this is important is because of what it suggests about how we read. Smaller parts of the text, instead of utilizing fewer aspects of the reading process, are instead miniature versions of what happens with the text as a whole. However, it would be a mistake to extend that reasoning to thinking that what we consider to be the act of reading applies equally to looking at a single, out-of-context word as it does to reading a whole text. That erroneous extension of the concept of self-similarity ignores the very important iterative aspect of self-similarity—that within and among these scale levels of text, eye movements demonstrate an interdependence on each other. Separating out a section of text would disrupt that interdependence—what we think of as context. Weaver (1994) provided a succinct explanation of the interrelationship of all aspects of a text, explaining that there is a

> constant interplay between and among levels, with the processing being as much or more top-down (schemata to words or letters) as bottom-up (letters or words to schemata). That is, there is a simultaneous intra-and inter-level processing, with each level potentially affecting all other levels at virtually the same time. (p. 1196)

Such a complex intertwining of relationships among different levels and aspects of text contributes to the understanding that removing one of these aspects—the word, for example—for use as an assessment or teaching focus also removes necessary aspects of what makes it an authentic text and defeats the purpose of isolating it in the first place. The iterative, self-similar analogy of eye movements at different scale levels suggests that reading processes are interconnected and utilized holistically at every level.

Nonlinear processes

Intuitively, reading may seem a serial and linear process. After all, a glance at most texts demonstrates that the text itself is certainly presented serially, with letters and words proceeding from left to right, with no overlap or backtracking. Adams and Bruck (1995) provided an example of this view:

> The letters and words of the text are the basic data of reading. For skillful adult readers, meaningful text, regardless of its ease or difficulty, is read through what is essentially a left to right, line by line, word by word process. In general, skillful readers visually process virtually each individual letter of every word they read, translating print to speech as they go. They do so whether they are reading isolated words or meaningful connected text. They do so regardless of the semantic, syntactic, or orthographic predictability of what they are reading. (pp. 11–12).

If we think of the text as the data of reading, and of reading as a linear process, then the serial nature of the data should easily transfer to a linear understanding of the text, where the input is proportional to the output. Lorenz (1993) explained that

> A *linear* process is one in which, if a change in any variable at some initial time produces a change in the same or some other variable at some later time, twice as large a change at the same initial time will produce twice as large a change at the same later time.... A *nonlinear* process is simply one that is not completely linear [italics in original]. (p. 161)

The purpose of this section is to explore whether reading can be considered a linear process. The argument is made that the third aspect of chaos theory considered here, nonlinearity, can be related to the placement and order of eye movements during reading.

Reading as a nonlinear process

If reading is a linear system, the more data bits—words, for example—that are uploaded to the brain, the more complete the reader's comprehension should be. It is interesting, as noted earlier, that readers do not have access to a certain amount of visual data when they read; they typically do not fixate between 20% and 30% or more of the words in a text (Rayner, 1997). However, this does not imply that readers do not perceive the words that they skip. On the contrary, there is much evidence that semantic and syntactic contexts allow readers to perceive the skipped words (Ehrlich & Rayner, 1981; Rayner & Well, 1996) and feel as though they have clearly seen and read every word. Not all words are fixated, hence not all letters are visually processed. Yet perceptual processing happens—reading occurs—without much of the available letter and word information being used by the reader.

It is important to note that a given text cannot necessarily be understood by all readers when the same words are deleted. While readers can skip one third of the words in a text, the words that are skipped can vary greatly between readers, as it is individuals' own expectations and attention to context that allow them to skip words during the reading process, a phenomenon that has been well documented (e.g., Balota, Pollatsek, & Rayner, 1985; McClelland & O'Regan, 1981; Rayner & Well, 1996). For example, Fisher and Shebilske (1985) recorded the eye movements of one group of readers

reading a text and noted which words those readers tended not to fixate. They then deleted those words from the text and gave the modified text to another group of readers, who subsequently had a difficult time reading the text. Even though both groups were able to look at the same words in the text—one group actively skipped the words, while the other had those same words removed from the text—the group that skipped the words of their own accord had an easier time reading the text than the group that had the words taken out for them. So in a given group of readers who read a text with similar comprehension levels, it is likely that there will be a considerable amount of difference in their eye movement patterns (Rayner, 1998). Word skipping is a natural and universal aspect of the reading process and does not necessarily affect comprehension adversely. Clearly the input of letters and words in reading is not directly proportional to the output of comprehension.

As discussed earlier, it is important to consider that 10–15% of a reader's fixations are regressions, where readers move their eyes back to areas of the text they have already passed through. Regressions are made by all readers frequently and nondeliberately, in that they are usually not conscious decisions by the reader. This would seem to provide fairly strong evidence that readers do not need to progress through the text word by word during reading. When Hogaboam (1983) analyzed patterns of eye movements to ascertain exactly what was the default pattern, he found there was no single pattern, such as "fixate word <n> followed by fixate word <n+1>," which happened the majority of the time. He noted that "models of reading assuming this characterization of eye movements might be disregarding over three-fourths of the normal eye movement data" (p. 314). Regressions and word skipping are not aberrations in the reading process that can be dismissed as inconsequential but are instead integral parts of the process.

One reason it may make intuitive sense to think of regressions and word skipping as anomalies is that it's not obvious why those aspects of eye movements happen. The eye movements alone don't tell us why the reader regressed or skipped a word, or exactly what the reader comprehended when doing so. For that, eye movements must be supplemented with another comprehension measure (Just & Carpenter, 1984). Next, miscue analysis is combined with eye movement recording to provide a more thorough view of reader comprehension that demonstrates the nonlinearity of reading: that the input does not necessarily equal the output.

Eye movements and comprehension

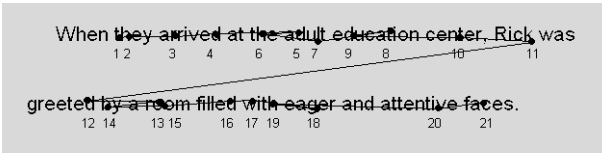
Recent research that combines eye movement recording with oral reading miscue analysis (Duckett, 2001; Freeman, 2001; Paulson, 2002; Paulson & Freeman, 2003) provides an informative view of reading processes on both the word and the text level. This approach is discussed here in order to provide insight about comprehending processes that correlate with eye movements to explore the analogy of nonlinearity in reading processes. Two examples are illustrated here: The first shows how a skilled teenage reader navigates a portion of text during a time when she makes no miscues, and the second demonstrates where the reader is looking when she makes an oral reading miscue.

Fixations and no miscues

If a reader makes no miscues—in other words, produces the text serially, and verbatim—does that imply that she or he views the text serially as well? In Figure 12, this reader made no miscues as she read aloud (the numbers beneath the dots indicate the order of fixations).

So what the reader read aloud was "When they arrived at the adult education center, Rick was greeted by a room filled with eager and attentive faces." (This is exactly what is written in the text.) However, note that her eye movements do not preserve that order. What she looked at while she read was "they they arrived arrived adult the adult education education center Rick greeted room by room filled with eager with attentive faces." Even when the text is orally produced verbatim, readers' eye movements do not necessarily proceed accordingly. Kolers (1976) explained that "in reading sentences, the visual system samples different parts of sentences at different times, but the perceiver does not necessarily run the sentence parts together in the mind in correspondence to the order in which they are sampled" (p. 390). Words that are fixated out of order are not necessarily perceived out of order—the input does not necessarily equal the output.

FIGURE 12
EYE MOVEMENT RECORD WITH NO ORAL READING MISCUES

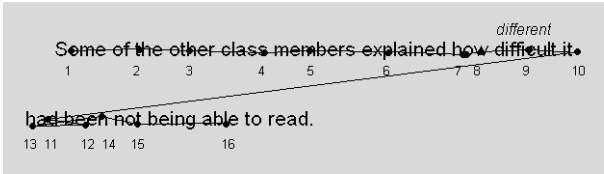


Fixations and miscues

Miscue analysis holds that readers make departures from the written text while reading, and these departures—sometimes called oral reading errors but in miscue analysis tradition referred to as miscues—provide insight to the text as the reader perceived it (Goodman & Goodman, 1994). Knowing that readers skip a third or more of the words in a text when they read, it might make intuitive sense that miscues are produced when, and perhaps because, readers skip words. For example, in Figure 13, an eye movement excerpt from the same reader who provided the example in Figure 12, the reader fixated three quarters of the words (and 76% of the words in the entire text). Intuitively, several words—*of, being, to*, and *read*—are good candidates for being miscued, because they were not looked at. However, in her oral reading of this portion of the text, the only miscue the reader made was a substitution of the word *different* for the text item *difficult*, a word she directly fixated:

Not only did this reader fixate the word she miscued, but she also did *not* miscue the words that she did *not* fixate. This is not an idiosyncratic or unusual phenomenon. In a recent study (Paulson, 2002), no significant difference was found between miscued words that were fixated and nonmiscued words that were fixated. That is, readers are as likely to fixate a word they miscue as they are to fixate a word they do not miscue. (For other examples similar to this one, see Paulson, 2002; Paulson & Freeman, 2003.) There is no linear relationship between fixation and perception—what is viewed is not necessarily what is perceived, and vice versa.

FIGURE 13
EYE MOVEMENT RECORD WITH ORAL READING MISCUE SHOWN



Eye movements display characteristics of nonlinearity

In addition to those examples discussed here, other eye movement measures can further the analogy of nonlinearity in reading. For example, the number of letters in a word is not the deciding factor in determining the duration of a fixation on that word because letters are not processed serially en route to forming a word. This fact, demonstrated experimentally at least by the early 1900s (Huey, 1908/1968), has been further supported by more recent eye movement research (Rayner & Pollatsek, 1989).

Nonlinearity describes an effect disproportionate to the cause. Reading a word 2 times will not result in twice the comprehension, and reading a word 10 times will not result in 10 times the comprehension. As this section illustrated, proficient readers can look directly at a word and nondeliberately miscue that word while reading aloud. Likewise, words that are not looked at are often perceived and read verbatim to the text. The process of reading is not analogous to linearity, either on the word, sentence, or text level.

Discussion

In this theoretical article, I argue that when related to chaos theory as an analogy, the reading process demonstrates characteristics of sensitive dependence, fractal self-similarity, and nonlinearity. Chaos theory suggests that reading is like the weather—we know the parameters that define most systems on a global level, but within those parameters it is not possible to predict the exact nature of the process on a local level. This is important for several reasons, one of which is that it is not possible to predict what an individual reader will comprehend or do at any given point in time. From a pedagogical standpoint, this would seem to argue against predetermined, scripted reading agendas that rely on uniformity in reading readiness and progress across readers.

Still, the issue may not be what we can predict, but rather what we can understand about reading processes by using a chaos theory analogy. Mandelbrot's (1999) stock market illustration is a good example—while it is impossible to predict the exact price of a particular stock on a given day, chaos theory reveals holistic patterns that are evident in its fluctuations over an hour, a day, a week, a month, and a year. Similarly, we can't predict exactly how a reader will read a specific part of the text, but we can better understand how the reader will make sense of that section in relation to the whole text. And when we examine the eye movements of a reader at every level of text, we find a process focused on the efficient construction of meaning.

Yet there is an intuitive understanding of the role of the eyes in reading that would explain their

purpose as moving deliberately and thoroughly to scan every letter of every word in order to provide the brain with all the text data on the page (e.g., Adams, 1990; Grossen, 1997; Pressley, 1998). Indeed, physiologically, this assumption makes sense. The eye is capable of uploading print information to the brain at the rate of 4 to 6 in-focus letters per 100 millisecond fixation, including the time needed to move from one word to the other. A very regular fixation pattern should get the job done—fixating every word once for 100 milliseconds would move the reader through the text at the very respectable clip of 600 words per minute. That's a fast rate, and if that process worked, readers would no doubt be doing it. But they are not. Instead, readers regress when they encounter areas of the text that are confusing (Bouma & Devoogd, 1974; Buswell, 1920; Just & Carpenter, 1980; Shebilske & Fisher, 1983), or if they haven't understood a word or words (Engbert et al., 2002; Vitu & McConkie, 2000). Some words are fixated more than once if they are unfamiliar, unexpected, or don't fit with other parts of the text (Balota et al., 1985), and, conversely, some words are skipped completely if they are constrained by the context and expected by the reader (Reichle et al., 1998). Likewise, if a word is expected by the reader yet still fixated, it is fixated for a shorter time than a word that is unfamiliar or unexpected (Ehrlich & Rayner, 1981; Rayner & Well, 1996). When confronted with difficulties, readers are very accurately able to send their eyes back to that part of the text that caused them difficulty (Rayner, 1998). In the same way, they tend to aim their fixations toward informative parts of a word, usually between the beginning and middle letters of the word (Rayner, 1979). And these are just some of the eye movements readers make and some of the reasons why readers make them. (For a thorough review of eye movements in reading, see Rayner, 1998.)

Virtually all the references to and examples of eye movements in this article paint a picture of a process focused on the efficient construction of meaning. Readers' eyes do not move relentlessly forward but go backward at times, fixate some words more than once, skip some words altogether, spend a small portion of time on some words and a large portion of time on others, and even examine different parts of different words. Instead of a serial data-uploading model, eye movement research points to the reader searching for information to aid in the construction of meaning. This difference may be subtle, but it is important. In general, what we find is that the search for meaning is a driving force behind eye movements that can help explain different eye movement patterns. This driving force can be represented by an attractor in a chaotic system.

Scientists usually plot attractors in "phase space"—a highly intuitive representation of a set of data points—in order to illustrate their patterns, because, as Briggs and Peat (1989) pointed out, "an attractor is a region of phase space which exerts a 'magnetic' appeal for a system, seemingly pulling the system toward it" (p. 36). The authors provide an illustration of an attractor in a nonchaotic system that supplements their definition:

> Imagine a hilly landscape surrounding a valley. Smooth round rocks will roll down the hills to the bottom of the valley. It doesn't much matter where the rocks start or how fast they're rolling, all eventually end at the bottom of the valley. (p. 36)

A phase space portrait of the hill-and-valley example would show a convergence on a single point—the bottom of the hill, where the system eventually comes to rest. This convergence is represented by an attractor. Because an attractor provides a representation of influences on the move toward equilibrium in a given system, it is often labeled in a way that allows a conceptualization of the influence it has on a system (e.g., Combs, 1996; Duke, 1994; Lorenz, 1993). For example, in the illustration described above, the attractor could be termed *gravity* because this is a major influence on what causes the rocks to move toward equilibrium, or a steady state, at the bottom of the hill. This example describes an attractor in a nonchaotic system, because gravity represents a move within a system toward a steady state that, once it is reached, remains steady; the rocks do not roll back up the hill. An attractor found in a chaotic system, on the other hand, is one that represents an influence in a system toward equilibrium that never completely settles down—like the climate attractor in the system we call weather, as Lorenz (1993) pointed out.

In the analogy constructed here, reading is portrayed as a chaotic system, and its attractor can be described as representing the search for meaning, where *meaning* is a state of equilibrium that the reading process moves toward. I'll term the attractor in reading *comprehending*, as opposed to *comprehension*, following Goodman and Goodman's (1994) distinction between processes during reading—comprehending—and the end product of having read something—comprehension. Like gravity in the example above, the process of comprehending represents the influences that drive the reading process.

Thus *comprehending* is the attractor around which eye movements converge.

The comprehending attractor illustrates patterns of eye movements as the reader attempts to make sense of print during the reading process. The patterns can be thought of as representations of the reader's focused probe of the text-based elements of the text–reader transaction that characterizes reading. During this transaction, the reader's stance, purpose, schema, and other aspects of the reader's cognitive and sociopsycholinguistic background interact with the printed text. As demonstrated in the section on self-similarity, the attractor in reading cannot be described as a regular progression of predictable fixation patterns and fixation durations. Rather, it varies, and, significantly, it varies as a function of text difficulty. The brain sends the eyes where it needs more information for the purpose of comprehending what it encounters in the text, where comprehending involves the process of construction of meaning in all its various facets, including reader-related specifics (such as individual schema activation and utilization) and text-related specifics (such as pronoun referents).

That the attractor in reading is a chaotic attractor, as opposed to a nonchaotic attractor, may be important. Nonlinear, dynamic, and iterative reading processes may contribute to the ability of readers to respond to new information, clarify ambiguous information, and correct misunderstandings during reading. Combs (1996) described this idea in terms of general cognitive adaptability:

> From a theoretical point of view, chaos protects a system from sticking in small grooves or attractors, and thus failing to find larger, more effective outcomes. For instance, a memory search can be thought of as a trip through neural "state space" in search of the correct memory attractor. If the system gets stuck in the attractor of a wrong solution, subsequent recall will be incorrect. What is needed is a process that keeps it from settling down too quickly in the first attractor basin that comes along. This process is chaos. (p. 409)

The point is not that chaotic processes *cause* the normal reading behaviors of responding and absorbing new or unexpected text items, but that readers' focus on meaning can be efficiently realized through a reading process that includes chaotic attributes, as measured by eye movements. Schmeisser et al. (2001) would concur; their work suggests that "the oculomotor behavior of subjects who read poorly is simplified and less free to vary or to adjust itself to task demands relative to the eye movements of normal readers" (p. 812). Flurkey's (1997) conceptualization of reading fluency as *flow* supports this idea from an oral reading fluency standpoint. Flurkey suggested that proficient readers use a greater variability in reading rate than do less proficient readers. Chaos may be a route to flexibility in reading; the ability to adapt and assimilate during the reading process.

Linking reading analogically to chaos theory can inform how we perceive "normal" reading. When looked at through the lens of chaos theory, reading is clearly not a process of plodding along the text at some regular, predetermined rate but is instead a process that ebbs and flows. This is not as unusual as it may seem; other systems depend on chaotic fluctuation in order to function properly as well. For example, the human heart is usually thought of as beating at a steady, regular rate, unless there is the onset of a heart attack or other malfunction. In fact, the heart beats in a chaotic pattern, and the onset of congestive heart failure is indicated by a change to a nonfractal beat (Ivanov et al., 1999). In the same way, within this analogy, "regular" reading may, in fact, be typified by chaotic patterns. If that is the case, an eye movement record that reveals a pattern of equal fixation durations on each word would signify a lack of comprehending, reading's chaotic attractor. Or, in another scenario, a lack of statistical self-similarity of words fixated at different scale levels might be an indication that a skimming or scanning process were taking place—in which the first sentence of a paragraph were read, but not the rest of the paragraph, for example—which would potentially eliminate certain kinds of scaling similarities.

Just as chaos theory demonstrates that variation and unpredictability are important when considering reading processes, from a research design standpoint chaos theory helps us understand that we need to proceed with great caution when attempting to attribute causality to any single variable we are investigating. Simple cause–effect relationships in literacy research may actually be more dependent on details previously considered insignificant than has been assumed. At minimum, we are reminded that the importance of thick description of educational contexts in research reports—research from all paradigms, experimental to case studies—is crucial in interpreting and applying that research. We may also find further support for research approaches that embrace change, instead of assuming there is none or that changes are negligible. For example, formative experiments are a relatively recent response to the shortcomings of more traditional qualitative and quantitative educational research designs (Jacob, 1992) and are characterized by addressing questions of change and adaptation during the data-gathering process (Oakley, 2003). A strength of the approach is that formative

experiments take into consideration how instructional interventions can be adapted in response to situations that arise in the educational context, and the focus is on a wide range of factors, events, and even unforeseen consequences of the research (Reinking & Watkins, 2000). The connections to chaos theory can easily be seen in key features of formative experiments, such as the idea that

> an important aspect of conducting a formative experiment is that a researcher must be especially attuned to unanticipated effects of the intervention—that is, effects that not only were not anticipated at the outset but that are not directly related to the pedagogical goal [and that] formative experiments acknowledge the complexity of educational environments and seek deep understandings within that complexity. (Reinking & Watkins, 1998, p. 468)

As yet, formative experiments are not a widely used research design in literacy research. Links to chaos theory may provide that approach with a useful theoretical foundation.

Gleick (1987) reported physicist Mitchell Feigenbaum's assertion that

> there's a fundamental presumption in physics that the way you understand the world is that you keep isolating its ingredients until you understand the stuff that you think is truly fundamental. Then you presume that the other things you don't understand are details. (p. 185)

Feigenbaum's point is that chaos theory demonstrates that what are sometimes considered "just details" affect the whole system. His comment pertained to physics, but we may make this same mistake in reading theory, research, and practice—of believing that what we can grasp, easily manipulate, and study is the only important part of reading. We have, at times, been guilty of carving up reading in order to study it, becoming successful at spotting things that correlate with good reading, then believing that that correlating aspect of reading must remain divorced from reading as a whole in order to be learned sufficiently well. The connections between reading processes and chaos theory made here bring that assumption into question. Larsen-Freeman (1997) found studying chaos theory helpful in furthering understandings of second-language learning, and other educators (e.g., Goff, 1998; Trygestad, 1997) have found an analogy of chaos theory helpful when thinking about curriculum planning in general. We may find the analogy of chaos applied to reading processes in this article useful when considering reading instruction as well.

Summary

In this theoretical article, I construct an analogy between reading processes and chaos theory. Principal aspects of chaos theory—sensitive dependence on initial conditions, fractal self-similarity, and nonlinearity—are related to aspects of reading as represented by eye movements. When viewed through the lens of chaos theory, reading can be described as a self-similar, nonlinear dynamical system sensitive to reader and text characteristics throughout the process. Research implications for understanding reading processes in this way include highlighting the need for research designs that incorporate variability and change into instructional interventions so that causality is not erroneously attributed to a single factor. Pedagogical implications include an understanding of typical reading as a process that, as evidenced by eye movements, ebbs and flows spatially and temporally across the text depending on the reader's moment-by-moment comprehension needs. On a holistic level, this process raises questions about the appropriateness of reading programs that assume a constant, predictable level of comprehension and development across all students.

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AUTHOR'S NOTE

A concern of one anonymous reviewer was that introducing concepts from a field somewhat removed from literacy research and education makes it difficult for readers of the journal to judge the appropriateness of the terminology and explanations made here. Another concern was whether the construction of this analogy could be misconstrued as providing evidence-based conclusions of chaos theory literally and mathematically describing aspects of reading processes.

One anonymous reviewer requested information about the apparatus used to collect eye movements illustrated in the figures in this study. The eye tracker is an Applied Science Laboratories Model 504 eye tracker (specifications at http://www.a-s-l.com/504_home.htm). The 504 uses a remote pan-tilt camera, which negates the need for a chin rest or bite bar, and records eye movements to within .5 degrees accuracy by tracking a reader's pupil and corneal reflection with an infrared source. All eye tracking participants whose eye movement excerpts were used as examples here were effective readers with vision correctable to 20/20. In all cases, after reading the texts aloud, each participant retold the story to ensure that basic levels of comprehension were met, as measured by miscue analysis procedures.

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