A scanpath measure reveals effects of age of reader and syntactic complexity of sentences.

Introduction
In reading, the eyes usually move in one direction from word to word. However, it is well-known that the eyes sometimes deviate from this regular trajectory: easy words, e.g. functions words, are often skipped and words that are hard to interpret into the sentence context can induce regressions (see Rayner, 1998, and Clifton, Staub, Rayner, 2007, for reviews). Also, fixation patterns change as readers age: older readers skip and regress more often while younger readers have a more regular left-to-right gaze trajectory (Laubrock, Kliegl, Engbert, 2006). All these phenomena have so far mostly been investigated using word-based measures like the probability to skip a word or to regress from it. Larger fixation sequences have received little attention, in part due to a lack of appropriate tools for data analysis of such sequences. Von der Malsburg & Vasishth (2011) introduced a measure that quantifies the similarity of two scanpaths based on spatial and temporal differences. They used this measure for a cluster analysis of regression patterns in garden-path sentences and identified different processing strategies that were conflated in word-based measures.

Here, we use this measure to analyze a large corpus of eye movements recorded from 230 participants who read 144 simple German sentences each (Kliegl, Grabner, Rolfs, Engbert, 2004). The goal was to see whether the scanpath measure could reveal the scanpaths effects to which the literature hinted. The predictions were: i) Sentences that are linguistically more difficult to process elicit more complex scanpaths. ii) Scanpaths recorded from older readers are more complex than scanpath by young readers. Sentence difficulty was quantified by two theories of sentence processing, a variant of surprisal theory (Boston, Hale, Vasishth, Kliegl, 2011) and cue-based parsing theory (Lewis & Vasishth, 2005).

Material
The 144 sentences in the corpus where simple and short (mean number of words: 7.9, sd: 1.4). See figure 1 for two examples. The participants came from diverse socioeconomic backgrounds. Young readers were on average 25.9 years old (sd: 7.9) and old readers were 68.8 (sd: 5.6). For this analysis we used the data of all 72 old readers and of a random subset of 72 young readers.

Method
For a sentence we calculated all pair-wise similarities of the recorded scanpaths using the Scasim measures introduced by von der Malsburg & Vasishth (2011). Multidimensional scaling (Kruskal 1964) was used to fit a map of the scanpaths on which similar scanpaths are close together and dissimilar scanpaths far apart. Mixture of Gaussian modeling was used to calculate a density function for this map (Fraley & Raftery, 2002, 2006). The measure of complexity of a scanpath was the density of the map at the point where the scanpath was located. This procedure was repeated for all 144 sentences in the corpus. A sentence that elicits more diverse scanpath patterns has a map of scanpaths that is more spread and hence the average density is lower (fig. 2).

A linear mixed model was used to model the complexity scores of scanpaths as a function of (i) age of reader (continuous), (ii) difficulty of the sentences according to surprisal theory, and (iii) cue-based retrieval theory and (iv) all two-way interactions of age, surprisal and retrieval. The model also included random intercepts for participants and sentences.

Results
Age, surprisal and retrieval all had significant effects on scanpath complexity: the older the reader, the more idiosyncratic his/her scanpath pattern. The more difficult a sentence (according to mean surprisal and retrieval), the more complex and diverse the scanpaths recorded for that sentence. Age interacted with surprisal and retrieval: the older the reader, the weaker the effects of surprisal and retrieval. See figure 3.

Summary
This is, to our knowledge, the first demonstration of the use of a scanpath measure to test predictions for scanpath complexity in reading. All predictions were confirmed. Additionally, we found that surprisal and retrieval effects are weaker in older readers suggesting an increase in canonical reading or mind wandering. All sentences were relatively simple showing that scanpath analyzes of the kind used here are sensitive even to subtle effects.

Figure 1: Scapan path patterns from two sentences. Left, scanpaths from the sentence that elicited the most regular scanpaths: "Wolfgang Töchter studieren Literatur und Maschinenbau." (Wolfgang's daughters study literature and engineering.) Right, scanpaths from the sentence that elicited the most irregular scanpaths: "Den Ton gab der Künstler seinem Gehilfen." (The artist gave the clay to his apprentice.) The first sentence has canonical word order and long words (less oculo-motor effort?). The second sentence has non-canonical word order and a lexical ambiguity. ("Ton" can mean clay or sound.) Also the words are short in the second sentence which may lead to more misplaced fixations.

Figure 2: Maps of scanpaths for the two sentences discussed in figure 1. Left, the map for the simple sentence with a relatively small spread of scanpaths and areas of high density. Right, the map for the difficult sentence with relatively more spread of points and the arrows point to examples of simple (57, 192) and complex scanpaths (22, 193).

Figure 3: Estimated effects of age, surprisal, retrieval and their interactions on scanpath complexity (as quantified by scanpath density on the maps of scanpaths). Intervals are 95% confidence intervals.