Does the movement pattern of non-visual eye movement during episodic vs semantic memory tasks correspond to Lévy Flights?

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Background

Non-visual eye movements (NVEMs) during recall give insight into mental processes (Hiscock and Bergstrom, 1981; Ehrlichman et al., 2007). Fixations have been mapped to active recall and saccades to mental search (El Haj and Lenoble, 2018; Ferreira et al., 2008). As such NVEMs seem to correlate the traversal of mental space during recall, with saccades showing the path.

Explicit recall is part of the *declarative memory* system comprised of episodic and semantic recall as well as future imagery. We examined whether activation of different forms of declarative memory cause different patterns in the NVEMs.

Furthermore, searching for memories in the mental space can be related to foraging for resources in the physical world. Since foraging is time consuming and energy costly it is likely that the pattern of NVEMs has some underlying *strategy*. One search strategy, which can optimize efficiency, are Lévy Flights with a step length corresponding to a Lévy distribution (Viswanathan et al., 2000):

$p(x) \sim x^{-\alpha}$ with an exponent of $1 < \alpha < 3$

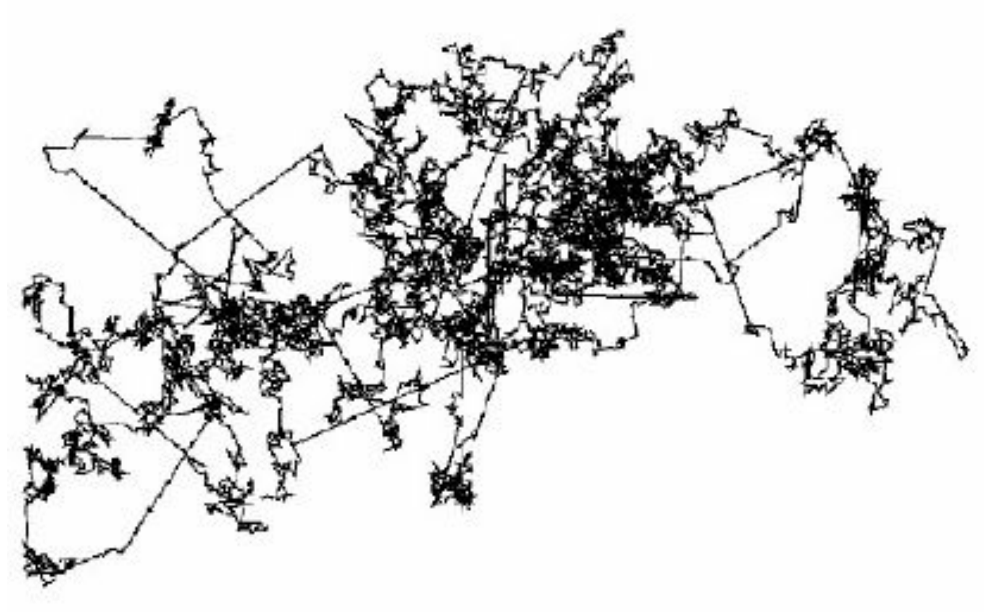

Figure 1: Trajectory of a Lévy Flight (Chechkin 2008)

Objective

To examine if there are differences in the patterns of NVEMs during different memory types and if there is some underlying strategy, we investigated the spatio-temporal distribution of the NVEMs during episodic and semantic memory tasks and calculated their correspondence to Lévy Flights.

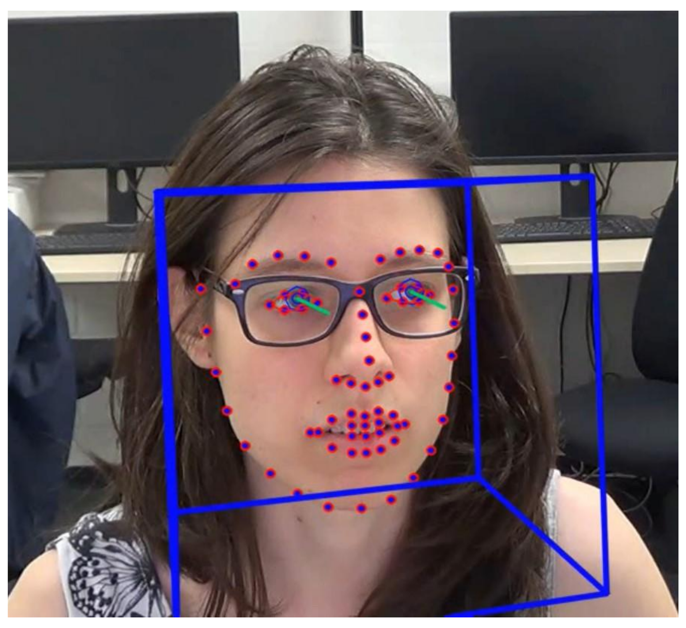

Figure 2: Visual output of OpenFace (Baltrusaitis, 2018), with the eye-gaze vectors in green

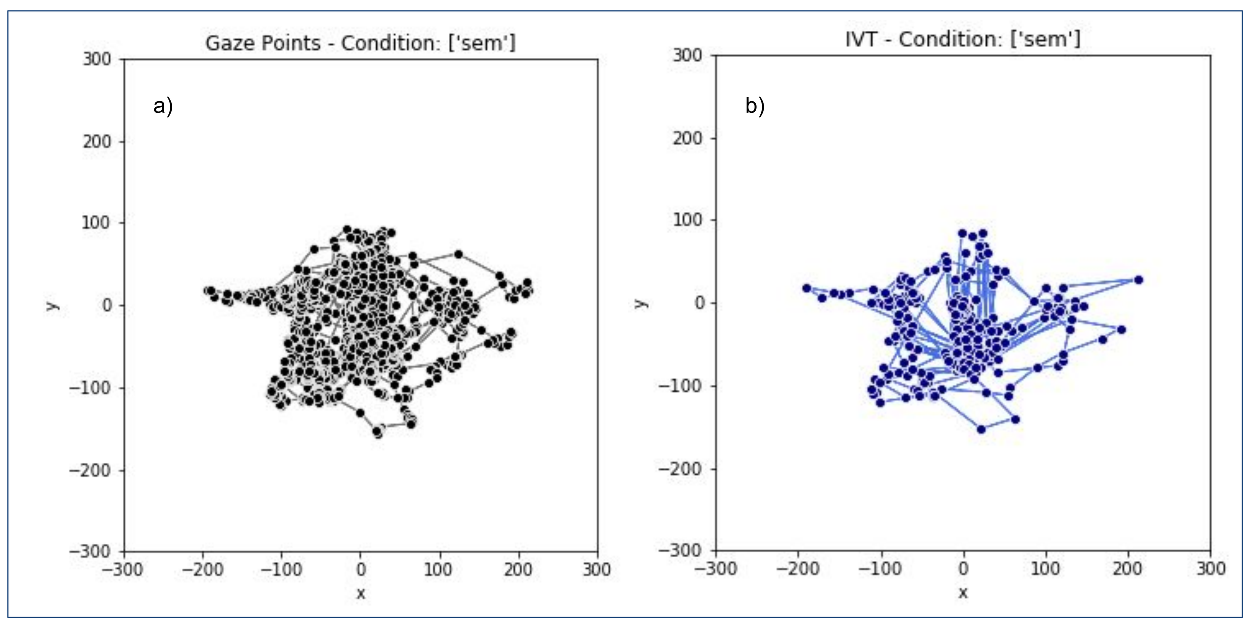

Figure 3: a) Visual path of raw gaze points and b) fixations of Subject 4 for the memory condition "semantic"

Method

1) Extracting raw NVEM data from the videos using the open source tool OpenFace (Figure 2)
2) Classification of fixations in raw NVEM data (Figure 3)
3) Calculation of the distance between fixations
4) Graphically fitting Lévy, lognormal, gamma, power law and normal distribution to the distance data for the individual memory conditions (Figure 4)
5) Calculation of Akaike's Information Criterion (AIC) for all distributions (Table 1)
6) Calculation of a lower boundary dist_min via maximum likelihood estimate for the power law (Table 2)
7) Fitting the power law and lognormal distribution to the data above the lower boundary

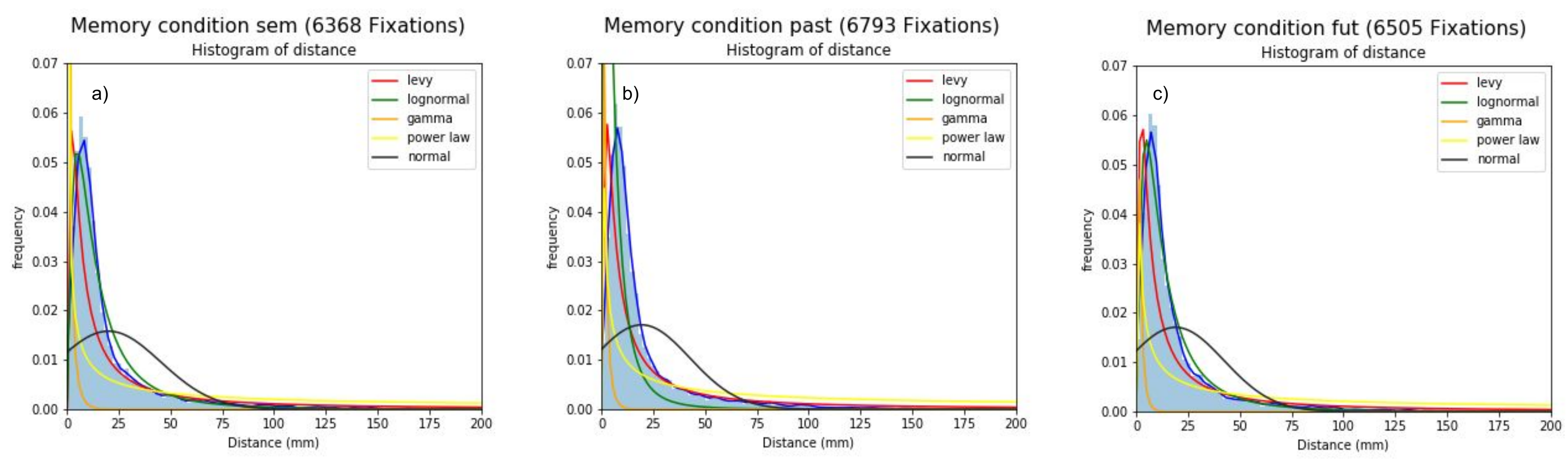

Figure 4: Lévy, lognormal, gamma, power law and normal distribution fit to the distance data for the a) semantic b) past and c) future memory conditions

Results

All memory conditions show a similarly positively skewed distribution for the saccade distance.

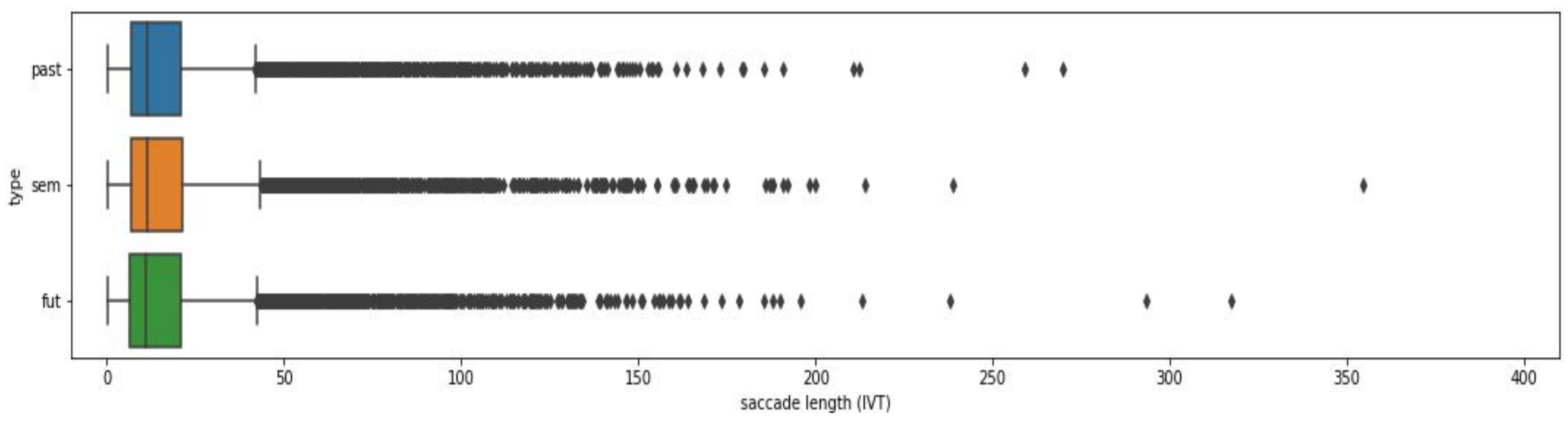

Figure 5: Boxplots of the calculated saccade distance of all participants for the three memory conditions (past, semantic, future)

AIC indicates that the lognormal distribution fits the data for each memory condition best.

Akaike's Information Criterion					
	normal	lognormal	gamma	Lévy	Power law
semantic	59192.43	49608.06	53080.16	53080.16	60350.53
past	62086.98	52471.24	53471.73	56736.73	56341.56
future	59474.35	50026.20	51213.00	53619.89	60634.27

Table 1: Akaike's Information Criterion for the fit of the normal, lognormal, gamma, lévy and power law distribution onto the whole data

A small estimated lower boundary for the data leads to a power law with an exponent in Lévy range ($1 < \alpha < 3$)

Fitting the power law to the tail-data			
	Semantic	past	future
Lower boundary	9.173592	9.654288	138.8049
α	2.16	2.21	6.38

Table 2: Bootstrapped minimum distance and exponent to maximize the goodness of fit of a power law distribution to the saccade tail-data

A power law distribution fits the data above an estimated lower boundary better than a lognormal distribution for all memory conditions.

Vuong Test			
	semantic	past	future
one-sided	1	1	0.4656
two-sided	2.5571e-20	3.3346e-19	0.9312

Table 3: Vuong Test to check if both the power law and the lognormal distribution are equally far from the true tail-distribution (two-sided) and if the power law function is the better fitting tail-distribution (one-sided)

Conclusion

- Similar results across the three memory conditions lead to the conclusion that the memory retrieval process embodied by NVEM seems to be the same for all forms of declarative memory on some fundamental level.
- Since both the power law and the lognormal distribution are heavy tailed distribution, we can assume that heavy tailed distributions play a role in memory recall.

Limitations

- While the NVEM was recorded during memory tasks the connection between the content of the recall and NVEMs has still to be made.
- The recording frequency of the NVEM is quite low with 25 Hz which may decrease the accuracy of the fixation identification
- OpenFace underestimates extreme eye-movements as such the raw NVEM data underestimates the actual NVEM and the fixations are closer together

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