

Heterogenous human dynamics in intra- and inter-day time scales

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Abstract – In this paper, we study two large data sets containing the information of two different human behaviors: blog-posting and wiki-revising. In both cases, the interevent time distributions decay as power laws at both individual and population level. Unlike previous studies, we put emphasis on time scales and obtain heterogeneous decay exponents in the intra- and inter-day range for the same dataset. Moreover, we observe opposite trend of exponents in relation to individual *Activity*. Further investigations show that the presence of intra-day activities mask the correlation between consecutive inter-day activities and lead to an underestimate of *Memory*, which explain the contradicting results in recent empirical studies. Removal of data in intra-day range reveals the high values of *Memory* and lead us to convergent results between wiki-revising and blog-posting.

Introduction. – Thanks to the development of the information technology, comprehensive data available from the internet give us valuable insights into the pattern of human behaviors. Many recent studies of human behavior focus on the distributions of inter-event time or waiting time and report a heavy-tail both at the individual and population level. Examples of empirical studies including communication patterns of electronic mails [1–4] and surface mail [4,5], web surfing [6,7], short message [8], online game [9,10] and movie rating [11].

In all the above systems, the observed distributions of interevent time go as τ^α with exponents ranging from 1 to 3. Various mechanisms were suggested to explain the underlying dynamics. One main class of mechanism is the priority-queue model [1,2], which yields power law waiting-time distributions $p(\tau) = \tau^{-a}$ with universal exponents $a = 1.0$ and 1.5 . Other mechanisms include the adaptive interesting model [12], the memory model [13] and the interaction model [14]. A crucial assumption of all these models and empirical studies is that the mechanisms driving human behaviors are identical in all time scales. According to this assumption, interevent time with length in minutes and in days are generated by the

same mechanism and follow the same scaling law. Even in the cascading nonhomogeneous Poisson process [3,4] which emphasizes external factors such as circadian and weekly cycles, the distributions still follow power laws with identical exponent over the whole range.

Table 1 shows a collection of recent empirical results, including the exponents and the unit of interevent time and the time range where the power laws were observed. In this table, we simply classify the results into intra- and inter-day behaviors. As we can see, for those data with unit in second or minute, the studies are often focused on the intra-day interevent time distribution; for those with unit in hour or day, only the inter-day range was studied. None of these studies investigated both the intra and inter-day behavior, though some noticed a hump in the interevent time distribution caused by the circadian rhythm [15]. One case that had been studied intensively is email and letter based communications, where some studies suggested that mechanisms of the two activities are different, based on the different exponents observed [2]; others suggested that the two are essentially the same based on the data collapse of interevent time distributions [4]. Limited attention has been paid on the different time ranges in the two activities, as the timestamp of email and letters communications are, respectively, in the unit of second and day, and exponents are thus extracted from different time range.

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Table 1: Comparison of the exponents from different human activities. The unit of interevent times and the time range in these studies are shown in the table. * corresponds to the average of exponents from individual distributions; Δ corresponds to the exponent from a single user; the others are the ones from global distribution.

Human activity	Unit	Range	Exponent
Email [2,13]	s	intra-day	1*, 0.9
Correspondence [13,16]	day	inter-day	2.37 Δ , 2.1 Δ
Library loans [2]	min	intra-day	1*
Printing behavior [17]	s	intra-day	1.3 Δ
Visits of a web portal [2]	s	intra-day	1*
Visits to the same URL [6]	s	intra-day	1
Visits to any page [6]	s	intra-day	1.25
Queries on AOL [7]	hour	inter-day	1.9
Message on Ebay [7]	hour	inter-day	1.9
Logging actions on Wikipedia [7]	hour	inter-day	1.2
Movie rating [11]	day	inter-day	2.08

By comparing the activities in the table, we find that the inter-day exponents tend to be clearly higher than the intra-day ones: the exponents of four of the five inter-day activities are around or more than 2; all the exponents of the six intra-day activities are around or a little more than 1. However, it is, of course, insufficient to prove the above relationship only by comparison between the exponents of different activities.

Early work on intertrade time in stock market also shows different correlation between intra- and inter-day behavior [18]. However, the dataset examined in this studies correspond to the time interval between consecutive trading, not necessarily by the same trader. In other words the time interval does not characterize the behavior of a single trader but rather a population of traders. It is still hard to tell whether the individual behavior in intra- and inter-day range are also different.

We thus aim to bring further evidence in this paper. Our work is based on two data sets from different sources which record two kinds of human activities: wiki page revising and blog posting [19]. The heavy-tails are found in both intra- and inter-day part of the distributions from these two activities. Our results show that even for the same activity the exponents of these two ranges are different.

Further evidences are obtained by examining the dependence of decay exponent on individual *Activity*, the measure of how frequent the action is taken. Zhou *et al.* [11] found that the exponent increases with *Activity*, which was further confirmed by Radicchi [7]. It is noted that both analyses are conducted in the inter-day range. In our case, we found the same dependence in the inter-day range but remarkably a different behavior in the intra-day range. It further demonstrates that the mechanisms underlying intra- and inter-day human dynamics are different.

On the other hand, weak memory in human behaviors are observed in system such as library loans and printing [20]. However, other studies show significant memory in some systems driven by human [17,19,21,22]. For wiki

page revision, we found seemingly weak memory. However, we observe a strong memory comparable to that of blog-posting [19] by removal of intra-day intervals and consider the inter-day ones only. It shows that the memory of inter-day activities is underestimated as intra-day activity mask the correlation between inter-day activities in analysis. We suggest that it is the reason behind the apparent weak memory in some human behaviors.

Data sets description. –

Wikipedia. Wikipedia (Wiki) is a free encyclopedia written in multiple languages and collaboratively created by volunteers. Wiki contains millions of articles which is produced by ten thousand of online volunteers. When an article is revised by a user, a new version is created by this user. The database we consider contains the timestamp and the authors of all the revisions in the Chinese Wiki. This data set is composed of 9641842 revisions made by 81823 users between 26/10/2002 and 7/6/2009.

Blog. Blog is a kind of so-called web2.0 applications emerging in recent years, on which people post, read and comment articles from each other [23,24]. Our data was collected from the campus blog website of Nanjing university (<http://bbs.nju.edu.cn/blogall>). Most users are current or former students and teachers of Nanjing university. As of 01/09/2009, there are 1627697 articles posted by 20379 users in this website. The first post is at 25/03/2003 when the blog was established.

Empirical analysis. –

The global distribution of interevent time in intra-day and inter-day range. The timestamps of both data sets are in precision of one minute. Here, the interevent time τ is the time interval between consecutive actions, *i.e.* revising a wiki-page by the same user in wiki or posting an article by the same user in blog. The global distributions of τ for both data sets are shown in fig. 1. As we can see, the distributions can be divided into two parts: For the intra-day range, the curves clearly show the heavy

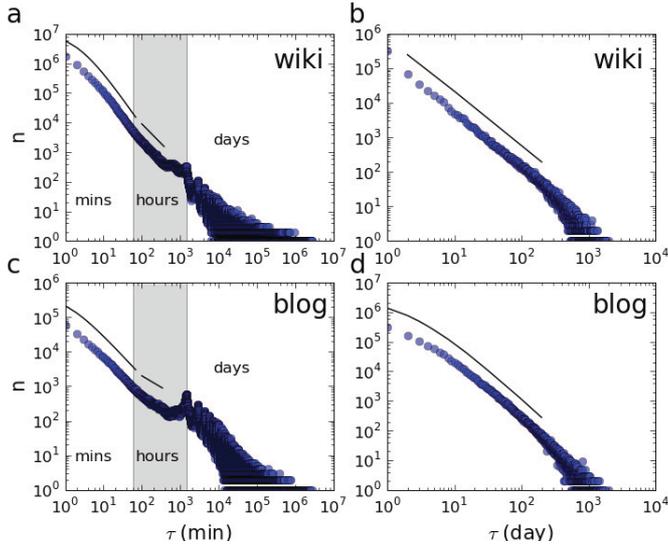


Fig. 1: (Color online) The global distribution of interevent time spanning the intra- and inter-day range. n is the frequency. We fit the distributions with the “shifted power law”: $y \sim (x + a)^{-\beta}$ [25]. Panels (a) and (c) show the distributions of the intra-day range of wiki-revising and blog-posting; panels (b) and (d) show the inter-day range. The decay exponents are $\beta_{mins} \simeq 1.88$ and $\beta_{hours} \simeq 1.32$ in (a), $\beta_{mins} \simeq 1.20$ and $\beta_{hours} \simeq 0.66$ in (c); $\beta \simeq 1.57$ in (b), $\beta \simeq 2.02$ in (d).

tails; for the inter-day range, they all show oscillations because of the circadian periodicity that make it hard to observe the scaling law.

Even in the intra-day range, the power law behavior is not homogeneous in all time scales and a slight hump is observed at $\tau \approx 100$ (see fig. 1(a) and (c) and fig. 4 for clearer evidence). We thus apply a piecewise fitting curve to show the change in power law exponents. For the range with $\tau < 100$ (within about 1 hour), the exponents of blogging and wiki-revising activities are 1.20 and 1.88; for the range with $\tau > 100$ (beyond 1 hour and within 1 day), lower values of 0.66 and 1.32 are found.

Figures 1(b) and (d) show the distribution of inter-day interevent time where a unit of one day is employed to eliminate the oscillation. The heavy tails in the inter-day range are shown clearly in these two distribution. The exponent of blogging activity is 2.02 which is significantly higher than the ones in intra-day range, in agreement with the results obtained by comparing different empirical studies in table 1. On the other hand, the intra-day exponent of wiki-revising seems to be close to the inter-day one. However, as we will see in following section, the empirical analysis at group and individual levels demonstrate the different activity pattern between the two ranges.

Heterogeneous dependence on activity. In this section, we will investigate further the features of intra- and inter-day activity pattern. Firstly, we measure the average *Activity* A_i of user i as $A_i = n_i/d_i$, where n_i is the

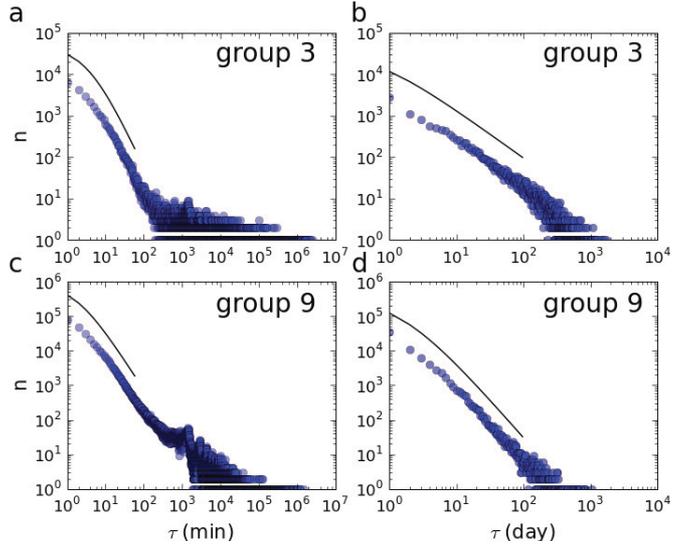


Fig. 2: (Color online) The interevent time distribution of wiki-revising at a group level (group 3 and group 9). For distribution in the intra-day range, the range of fitting is from 1 to 70. (a) and (c) correspond to the intra-day range and (b) and (d) correspond to the inter-day range. The decay exponents are $\beta \simeq 2.00$ in (a), $\beta \simeq 1.16$ in (b), $\beta \simeq 1.75$ in (c), $\beta \simeq 2.21$ in (d).

total number of actions of user i and d_i is the time between the first and the last actions. We then sort users in an ascending order of *Activity* and divide the entire population into 10 groups, each of which have M users ($M \approx N/10$ where N is the total number of users). The first M users in the list belong to group 1, and the last M users are belong to group 10, etc. We only consider users with $n_i, d_i > 10$. For wiki, there are 14410 qualified users and $M = 1400$; for blog, there are 12827 qualified users and $M = 1300$. As different from previous studies [7,11] which only focus on the inter-day range, we investigate the dependence of the exponent on *Activity* in both the intra- and inter-day range. In fig. 2, we plot the interevent time distribution of wiki for group 3 and 9 (which, respectively, correspond to average *Activity* $\langle A \rangle = 0.07, 1.12$). For the inter-day range, we get the same dependence as the one obtained in other inter-day activities: the exponents increase with *Activity*. Some exponents of inter-day activities are small such as the one in logging action probably due to the relatively low *Activity* [7]. For the intra-day range, this dependence is totally different: the exponents decrease with increasing *Activity* and the change is relatively smooth. In fig. 3, we plot the exponent of the interevent time distribution of wiki-revising and blog-posting as a function of *Activity*. Though the values of exponents are different in these two cases, they show the same features: the exponent and *Activity* are positively related in the inter-day part and negatively related in the intra-day one.

Interevent time distribution for individuals. To show further evidences for our conjecture, we look in details

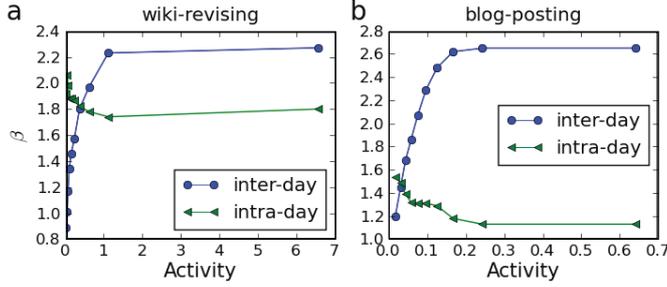


Fig. 3: (Color online) Dependence of decay exponents on *Activity*.

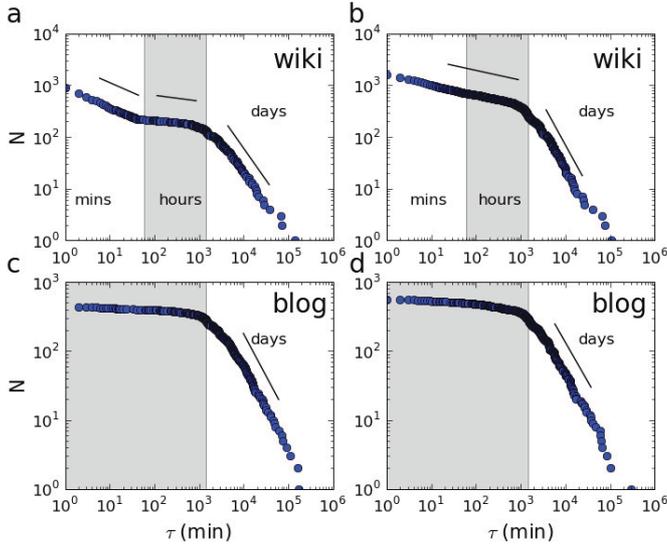


Fig. 4: (Color online) The cumulative distribution of interevent times of individuals. N is the cumulative frequency of intervals. User 1 and user 2 in (a) and (b) are from wiki; user 3 and user 4 in (c) and (d) are from blog. The decay exponents are $\beta_{mins} \simeq 0.38$, $\beta_{hours} \simeq 0.11$ and $\beta_{days} \simeq 1.23$ in (a), $\beta_{hours} \simeq 0.19$ and $\beta_{days} \simeq 1.57$ in (b); $\beta \simeq 1.22$ in (c), $\beta \simeq 1.13$ in (d).

the behavior of individual agents. Figure 4 shows the cumulative distribution of interevent time from four users, two are from the data set of wiki and two are from the blog data set. An obvious trend change is observed at $\tau \approx 1$ day. For the inter-day range, all these distributions follow power laws. The wiki users often revise one page many times within a day but blog users seldom post several articles in one day. Therefore, it is hard to study the intra-day activity of blog-posting at the individual level as data is insufficient in this range. For wiki-revising, the distributions are even heterogenous within the intra-day range (see fig. 4(a)), which is consistent with the global one and shows further complexity in the mechanism of human activity.

The consecutive interevent times of these users are plotted in fig. 5 which helps us to visualize the dynamics of their activities. For the blog user (see fig. 5(a)), we observe the clustering of extremely long interevent times which is also called mountain-valley-structure found in many

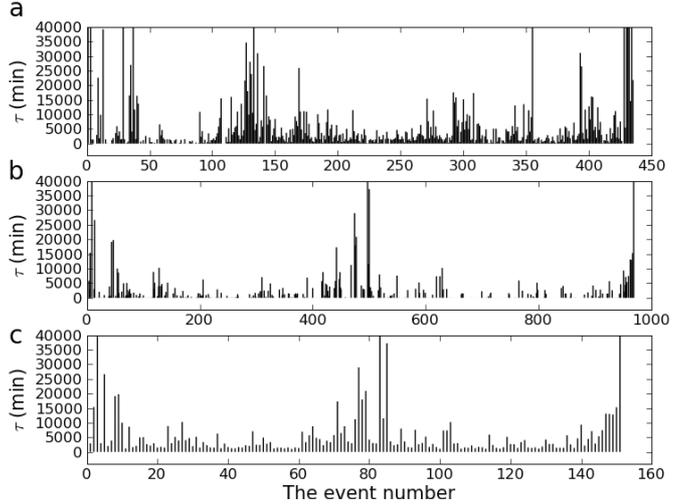


Fig. 5: The interevent time of consecutive events for (a) user 3 in fig. 4(c); (b) user 1 in fig. 4(a); (c) user 1 after deleting short interevent times which are less than 1000 min.

complex systems [26,27]. For the wiki user, fig. 5(b) shows similar clustering but the interevent time longer than one day are separated by many short intra-day interevent times which are rare in blog-posting (compared with fig. 5(a)). The consequence is that the autocorrelation of interevent time becomes rather small. This autocorrelation characterizes the *Memory* of individual behavior, as given by [20]

$$M_k = \frac{1}{n_\tau - 1} \sum_{i=1}^{n_\tau - 1} \frac{(\tau_i - m_1)(\tau_{i+k} - m_2)}{\sigma_1 \sigma_2}, \quad (1)$$

where τ_i is the interevent time values and n_τ is the number of interevent time and $m_1(m_2)$ and $\sigma_1(\sigma_2)$ are sample mean and sample standard deviation of τ_i 's (τ_{i+k} 's). The two interevent times τ_i and τ_{i+k} are separated by k events. The *Memory* M_1 of the blog user is 0.13 but the one of the wiki user is only 0.02.

The average M_k of all qualified users with k ranging from 1 to 35 is shown in fig. 6. Average M_1 of wiki-revising is 0.13 which is obviously less than 0.21, the M_1 in blog-posting. This result is in agreement with the one we found in fig. 5(a) and (b). As there are different mechanisms in human activity in the intra- and inter-day range, we find a way to study the memory of these mechanisms separately. We remove the interevent times of wiki-revising which are less than 1000 minutes (about 1 day) and analyze the remaining series which only contain the inter-day intervals. This allows us to consider only the memory in the inter-day intervals and ignore the actions within one day. Figure 5(c) shows the interevent time series after data removal, of which M_1 is 0.12. Correspondingly, we also find a significant increase in the average M_1 of wiki-revising through this procedure. As shown in the inset of fig. 6, average M_1 increases to 0.20 which is very close to the one in blog-posting. Moreover, the decay curve is similar to that

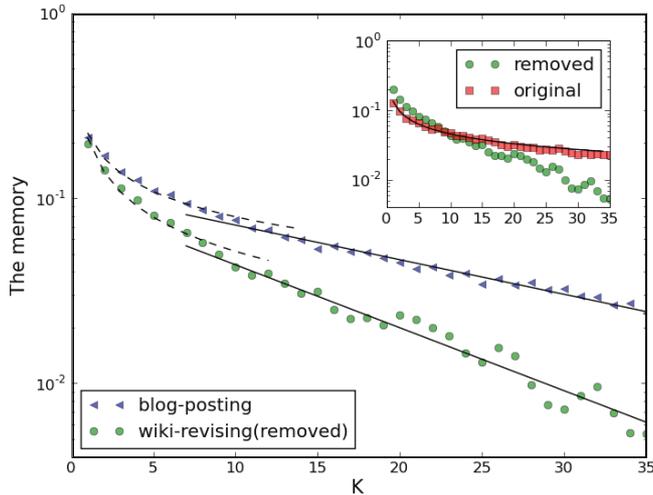


Fig. 6: (Color online) The average M_k of all qualified users in blog-posting and wiki-revising after data removal with different k . The comparison between the results before and after data removal is shown in the inset. For the one of blog-posting, M_k decays as a power law when $k < 10$: $M_k = 0.23 * k^{-0.45}$; when $k > 10$, it decays exponentially: $M_k = 0.1 * e^{-k/23.22}$ [19]. For the original data of wiki-revising, it decays as a power law over the whole range: $M_k = 0.13 * k^{-0.47}$. After data removal, when $k < 9$: $M_k = 0.61 * k^{-0.21}$; when $k > 9$: $M_k = 0.10 * e^{-k/12.76}$. To avoid characterizing users whose number of actions is too small, we consider only the qualified users of the two data sets and calculate the memory of all these users with k ranging from 1 to 35 (for wiki, a total of 809 users with number of revisions more than 800 and frequency of long intervals (>1000 min) more than 100 are considered; for blog, a total of 2126 users with more than 200 posts and frequency of long intervals (>1000 min) more than 200 are considered).

of blog-posting; when $k < 10$, it decays asymptotically as a power law; when $k > 10$, it decreased exponentially.

Further, we investigate the relationship between memory and *Activity* as we had done on the exponents of interevent time distribution. Using the same way above, we divide all qualified users of blog-posting and wiki-revising into 5 groups by *Activity* and get the memory of each group. Unlike the exponents, the memory of the two behaviors seems to be independent of *Activity*. For example, the average M_1 of three groups of blog users are 0.22, 0.21, 0.23 and the corresponding *Activity* are 0.12, 0.17, 0.28 per day.

Discussion. – We conclude by remarking two concrete evidences which support our conjecture that human activity patterns are significantly different in different time scales. Firstly, the exponents of interevent time distribution are different in the intra- and inter-day range. In addition to comparison with the previous empirical studies, we show difference at the individual and global level by investigating the activity patterns of wiki-revising and blog-posting. The second evidence is the different dependence on *Activity*: for the inter-day range, the exponents

increase with *Activity*; for the intra-day range, the exponents decrease with *Activity* and in smaller magnitude. On the other hand, we show the behavioral similarity between wiki-revising and blog-posting as the same exponent dependence is observed in corresponding range. This similarity further increases after removal of the intra-day interevent times of wiki-revising. Previous study reported the lack of memory in human activity but our work shows that the presence of intra-day activities mask the correlation between consecutive inter-day activities and lead to an underestimate of memory. Can we thus classify human activities by the interevent time scale? How to accurately measure the memory in a series which is complex and heavy-tailed? Further investigations are required in these directions.

In our previous studies [19], the temporal-preference model, which was suggested to describe blog-posting, is also suitable for wiki-revising in the inter-day range since it successfully generates similar exponent dependence on *Activity* and a significant memory. There are two main rules in the model [19]: 1) the more the user performs an activity recently, the more likely he will do it next; 2) there exists occasions that users choose what to do randomly with independent probability. We can understand the strong memory based on the first rule which is also responsible for the heavy-tailed interevent time distribution. However, in this model, the actions of inactive users are more likely to follow the random rule which leads to a smaller exponent in their distributions.

For the smaller exponents in intra-day range, one possible explanation is the time scale in scheduling activities. We can plan our daily schedule carefully according to our personal preference but we hardly plan what to do every minute. Our actions in minutes are more stochastic which may lead to the broad intra-day distribution. Actually, the random walk in one dimension is already used to model human activity which lead to interevent time distributions with exponent 1.5 [28,29]. Moreover, the negative relation between the exponents and *Activity* shows that there is also a difference between the behavior of inactive and active users. The inactive users, for example inactive blog users, may tend to post several articles consecutively after a long idle period. So they would act again and again within short time and produce more short-time intervals, which makes the exponents of inter-day distribution greater. More direct measure on intra-day behavior can be found in the study of daily movement of the human wrist which shows that the distribution of human wrist activity is also heavy-tailed [30]. This result, from the other perspective, demonstrates the burstiness of human behavior in intra-day range as what we found in interevent time distribution of intra-day range.

We remark again the interesting behaviors in both the intra- and inter-day range. There are interesting details within both intra- and inter-day range. A slight hump is observed in $P(\tau)$ at $\tau \approx 1$ hours. For inter-day range, the decay of memory is power law when $k < 10$ and became

exponential beyond this range. Is there a relation between time units (such as minute, hour, week, month) and the dynamics underlying human activities? For example, trend change observed in $P(\tau)$ at one hour may due to the timing of tasks in hours.

Another interesting issue is the similar difference between the intra- and inter-day ranges on population behavior. In stock markets, the population behavior over time scales of days have stronger correlation than the one within a trading day and the correlation is also independent of the population *Activity* [18]. Similar results are found in the individual behavior according to our study: the distribution exponents, the *Memory* and the dependence on individual *Activity* are different in the intra- and inter-day ranges. Our results suggest that the difference of individual behaviors in the intra- and inter-day scales may be the origin of the observed features on the population behavior [18].

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