Two Types of Social Grooming
discovered in Primitive and Modern Communication Data-Sets

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Abstract

Social networking sites (SNS) provide innovative social bonding methods known as social grooming. These have drastically decreased time and distance constraints of social grooming. Here we show two type social grooming (elaborate social grooming and lightweight social grooming) discovered in a model constructed by thirty communication data-sets including face to face, SNS, mobile phones, and Chacma baboons. This demarcation is caused by a trade-off between the number and strength of social relationships on social grooming. The trade-off of elaborate social grooming is weaker than the trade-off of lightweight social grooming. On the other hand, the cost of elaborate methods is higher than lightweight methods. This model con-
nects micro-social grooming behaviour and macro-social structures with these trade-offs. People tend to use elaborate social grooming to reinforce close relationships and construct deep limited societies (e.g. face to face and Chacma baboons). This seems to be apriori. On the other hand, people tend to use lightweight social grooming to maintain many weak social relationships and construct expanded shallow societies (e.g. SNS). Humans recently have obtained this method. Humans with lightweight methods who live in significantly complex societies use various social grooming to effectively construct social relationships. Elaborate social grooming is for getting cooperation from close relationships. Lightweight social grooming is for getting information from many weak relationships.

Introduction

There is no room for doubt about a significant impact from the Internet on our social relationships. Especially, social networking sites (SNS) have dramatically decreased the limitations of time and distance in construction and maintenance of social relationships [1]. Additionally, SNS, which record all relationships and communications, should reduce people’s cognitive burden. As a result, weak social relationships (low frequent contact relationships) have increased [11, 12]. On the other hand, this technology has not seemed to affect the number of close relationships [13]. How have social structures changed?
Humans have diverse social relationships because these provide various advantages to them in complex societies. Close social relationships lead to mutual cooperation [14, 15, 16]. On the other hand, having many weak social relationships (weak ties) help in obtaining information, which is advantageous because weak social relationships where people rarely share knowledge often provide novel information [9, 10, 11].

The behaviour of constructing social relationships is called “social grooming,” which is not limited to humans but widely observed in primates [17, 18, 19, 7, 16, 4]. Humans use these different social grooming methods according to their strength of social relationships according to their time constraints [8, 4] (see also Fig. S1). Social grooming gives different impressions and has different effects on its recipients depending on its time and effort [1]. Communications in face to face and video calls get more satisfaction than communications in phone and text [20]. On Facebook, personal messages give more happiness than 1-click messages (like) and broadcast messages [21]. In other words, humans favor social grooming by elaborate methods (time-consuming and space constrained). Additionally, people in a close relationship tend to do these elaborate methods [8]. Furthermore, its positive effect in close relationships is larger than in weak social relationships [21].

Understanding changes by the appearance of SNS needs a model which explains various social structures by various social grooming including primitive methods and SNS communications. Sutcliffe et al. [22] constructed a model explaining the evolution of hierarchical social structures (like primates and some
animals), i.e. primitive social structures. These structures emerge by controlling a trade-off between foraging and social interaction. Song et al. [23] constructed a model which described macro-social network structures by micro-human attributes (social activity and social ability) by using four modern communication tool data-sets (an SNS, mobile phones, E-mails and a text messenger). Takano and Fukuda constructed a model which described trade-off between the number and strength of social relationships effects of modern communication tools (SNS, mobile phones, and SMS) to social structures [4]. However, these models do not explain the effect on social structures by primitive communications (e.g. face to face in humans and far cleaning in primates) and modern communications (e.g. SNS and mobile phones).

We construct a model of macro-social structures depending on micro-human behaviour extending the model in Takano and Fukuda [4] to connect modern communication and primitive communication. Social grooming behaviour is restricted by a trade-off between the number and strength of social relationships. This trade-off depends on social grooming methods. This model are led by common features of thirteen diverse communication data-sets including human primitive communications (face to face [2] and communications in a small community constructed by kin and friends [5]), modern communications (phone calls [2], E-mail [2], SNS [3, 4], and communications between unrelated people [6]), and non-human primate communications (Chacma baboons [7]). Comparing them should provide an understanding of social structure changes by appearances of novel communication systems (Fig. 1).
Results

We found two types of social grooming methods based on the trade-off between the number and strength of social relationships [24, 4] (Fig. 1). The one is “elaborate social grooming” which is by face to face and phones (Face to face (Pachur) and Phone (Pachur)), in kin and friends (Mobile phone (friends and family), SMS (friends and family)), and Chacma baboon social grooming (Baboon group A and B). This should be nearer to primitive human communications than the others. That is, these communications tend to bind humans with time and distance constraints or in primitive groups constructed by kin and friends. Another one is “lightweight social grooming” which is by SNS and E-mail (Twitter, 755 group chat, 755 wall communication, Ameba Pigg, and E-mail/Letter (Pachur)), and in relationships between unrelated people (Mobile phone (dormitory) and SMS (dormitory)). This has appeared in the modern age. These communications tend to unbind humans from time and distance constraints. This tends to be used with unrelated people. Details of data-sets noting in brackets are shown in Data-Sets section in Methods section.

Both were divided by parameter $a$ on $C_i = N_i m_i^a$ model [2] (Fig. 1), where $a$ shows strengths of the trade-off, individual $i$’s total social grooming cost $C_i$, $N_i$ is $i$’s the number of social relationships, $m_i$ is $i$’s mean strength of their social relationships ($m_i = \sum_{j=1}^{N_i} d_{ij}/N_i$), and $d_{ij}$ is the days on which $i$ does social grooming to individual $j$ (the strength of social relationships between $i$ and $j$). $a \neq 1$ suggests that social grooming behaviour depends on strength of social relationships because $a$ will be 1 when social grooming behaviour does
not relate to the strength of social relationships \( C_i = N_i m_i = \sum_{j=1}^{N_i} d_{ij} \).

\( a < 1 \) shows that people have stronger social relationships than when \( a = 1 \) because the effect of strong relationships (large \( m \)) to cost \( C \) is smaller than when \( a = 1 \) \( C = N m^a < \sum_{j=1}^{N_i} d_{ij} \) when \( m > 1 \). On the other hand, \( a < 1 \) shows that people have weaker social relationships than when \( a = 1 \) because of the effect of strong relationships (large \( m \)) to cost \( C \) is larger than when \( a = 1 \) \( C_i = N_i m_i^a > \sum_{j=1}^{N_i} d_{ij} \) when \( m > 1 \). We call the social grooming methods of \( a < 1 \) elaborate social grooming (Fig. 2h-m) and the methods of \( a > 1 \) lightweight social grooming (Fig. 2a-g). That is, the trade-off of elaborate social grooming between the number and strength of social relationships is smaller than that of lightweight social grooming. We estimated statistically parameter \( a \) of the data-sets by using a regression model \( \log N \sim Normal(-a \log m + b \log u, \sigma) \), where \( u \) is the number of days of participation for each person and \( \sigma \) is a standard deviation, that is, this assumed that a user’s total social grooming costs were equal to the number of days for which they had participated in the activity \( (C = u^b) \). Table S3 shows the details of this regression result.

This trade-off affected human social grooming behaviour. That is, people increased the amount of social grooming (i.e. time) with their strength of social relationships. \( a \) decreased the gradients \( \alpha \) which shows an increase of the amount of social grooming (Fig. 1b). Additionally, \( a \) changed people’s trends of social relationship constructions (Fig. 1a). People having limited and deep social relationships tended to do frequent social grooming (amount of social grooming was large) when \( a < 1 \). On the other hand, people having expanded and shallow
social relationships tended to do frequent social grooming when $a > 1$. We show these in the following.

Fig. S4, S5 and the previous work [4] show that the amount of social grooming from individual $i$ to individual $j$ tends to increase with the density of social grooming $w_{ij}$, where $w_{ij} = d_{ij}/t$ and $t$ is the number of elapsed days from the start of observation, i.e. the amount of social grooming did not depend on $t$. We modeled this phenomenon as linear increase which is the simplest assumption, that is, $v(w_{ij}) = \alpha w_{ij} + 1$, where $v(w_{ij})$ is the amount of social grooming and $\alpha$ is a parameter.

This assumption and the definition of $C_i = N_i m_i^a$ suggest a relationship between individual social relationship trends and their total amount of social grooming. $m_i$ shows individual $i$’s sociality trend (mean limitation and deepness of its social relationships) by the trade-off between $N$ and $m$. Amount of social grooming per day to reinforce social relationships describes

$$G(a, \alpha; C, m) = \alpha C (m^{1-a} - m^{-a})/T, \quad (1)$$

where $T$ is the number of days of the data periods (see section S1 for derivation). $\alpha$ was decided by the following simulation where an individual-based model was fitted to the data-sets. The amount of social grooming predicted by this equation showed a high correlation with the actual amount of social grooming in each data-set (S1). This equation shows that people who have large $m$ (i.e. limited and deep social relationships) have a large amount of social grooming when
doing elaborate social grooming ($a < 1$; Fig. 1). On the other hand, people who have small $m$ (i.e. expanded and shallow social relationships) have a large amount of social grooming when lightweight social grooming ($a > 1$). That is, $G(a, \alpha; C, m)$ shows that social grooming methods were used depending on the strength of social relationships (elaborate social grooming used for strong social relationships and lightweight social grooming used for weak social relationships). The threshold of both social grooming methods was $a = 1$. The amount of social grooming for construction with new social relationships $G_0$ does not depend on $a$ ($G_0 \approx N$; see section S1 for details).

We constructed an individual-based model to explore the effect of the trade-off parameter $a$ to social structures based on the monotonic increasing of $v(w_{ij})$ and the difference of the peak of $G(a, \alpha; C_i, m_i)$ depending on $a$ (see The Individual-based Simulation Model in Methods section for details and section S2 (a source code of this model)). Additionally, we assumed the Yule–Simon process on social grooming partner selection, because people basically do act this way [2, 4] (Fig. S3). In the model, individuals construct new social relationships and reinforce existing social relationships, where they pay their limited resources $G(a, \alpha; C_i, m_i)$ for the reinforcement.

First, we confirmed a consistency between $C = Nm^a$ and two assumptions of social grooming behaviour ($G(a, \alpha; C_i, m_i)$ and $v(w_{ij}) = \alpha w_{ij} + 1$) to fit the model to the data-sets optimized by $\alpha$ (see Experiment 1 section in Methods section). We used actual values of the data-sets as $a, T, C_i$ and $p_i$ in each simulation, where $p_i$ was the expected value of a new relationship each day.
\( p_i = (N_i - 1)/T \). \( a \) was the values in Fig. 2 and Table S3. \( T \) was the period for each data-set, and \( C \) was the 75th percentile of \( u^b \). \( N_i \) was given equally divided in a logarithmic scale \((N \in [1, T])\). This model fitted all data-sets (Fig. 3). We calculated the distributions of social relationship strengths \( d \) by using these fitted \( \alpha \) values with actual values of \( C_i \) and \( N_i \) (the number of individuals was 2,585). Their distributions of social relationships were roughly similar to actual distributions excluding Face to face (Pachur) (Fig. S6). That is, this model roughly has an explanation capacity for generating the process of social relationships depending on the trade-off constraint and human social grooming behaviour. The difference between the simulation result and Face to face (Pachur) data-set may have been because of the approximations of this model did not work with small \( a \).

Second, we analysed the effect of parameter \( a \) on the structure of social relationships by using the model (see Experiment 2 section in Methods section for details). Firstly, we fitted the model to each \( a \in [0.5, 2] \), where we used \( T \), \( C_i \) and \( N_i \) of the Twitter data-set settings in the former experiment. Secondly, we calculated the distributions of social relationship strengths \( d \) by using these \( \alpha \) on each \( a \), where we used actual \( T \), \( C_i \) and \( N_i \) of the Twitter data-set. We found that \( a \) changed the structures of social relationships and social behaviour parameter \( \alpha \) where the threshold was \( a = 1 \) (Fig. 4). The changes of \( a \) in \( a < 1 \) have a smaller effect on powerlaw coefficients \( \phi \) of social relationship strength than in \( a > 1 \). This shows that strong social relationships decreased in \( a > 1 \) because individuals having expanded and shallow social relationships have more
of the amount of social grooming than individuals having limited and deep social relationships \( G(a, \alpha; C, m); \) Fig. 1b). Additionally, \( \alpha \) in \( a < 1 \) was larger than \( \alpha \) in \( a > 1 \). Interestingly, \( \alpha \) was not effected much from \( a \) in range of \( a < 1 \) and \( a > 1 \), respectively. That is, individuals in \( a > 1 \) decreased the amount of social grooming \( v(w_{ij}) \) with close social relationships as compared to \( a < 1 \). As a result, the social structures were expanded and shallow in \( a > 1 \). It suggests that societies with lightweight social grooming had different properties when compared to societies with elaborate social grooming.

**Discussion**

We constructed a model of macro-social structures depending on micro-human behaviour restricted by a trade-off between the number and strength of social relationships depending on social grooming methods. This model is led by common features of thirteen diverse communication data-sets including human primitive communications, modern communication tools, and non-human primates. By analysing the model, we found two types of social grooming (elaborate social grooming and lightweight social grooming). They make different social structures. This is caused by people’s social grooming behaviour depending on the different trade-off between the number and the strength of social relationships. Both are separated by trade-off parameter \( a \) on \( C = Nm^a \) model \((a < 1: \text{elaborate social grooming, } a > 1: \text{lightweight social grooming})\). People tend to use elaborate social grooming in face to face communications and
communications in small communities constructed by kin and friends, i.e. the communities should be near primitive groups. Additionally, Chacma baboon data-sets also show a similar trend. They tend to use this social grooming to reinforce close social relationships. That is, elaborate social grooming is a primitive method (i.e. apriori). This may be used in non-human primates, primitive human societies, and close relationships of modern humans.

On the other hand, people tend to use lightweight social grooming in SNS, E-mail, and communications in communities constructed by unrelated people, i.e. the communities should be non-primitive groups. That is, this social grooming is posterior. People tend to use this to construct many weak social relationships. Social structures that use this method are significantly expanded and shallower than by elaborate social grooming. Accordingly, social structures may have changed significantly when people who maintain social relationships by elaborate social grooming have gotten lightweight social grooming.

Both also differ from a cost and effect perspective. The trade-off interacting close social relationships of elaborate methods is weaker than that of lightweight methods. On the other hand, the time and effort of lightweight methods are less than elaborate methods [25]. Social grooming with time and effort (elaborate social grooming) are effective to construct close social relationships [25, 20, 21]. Therefore, elaborate methods are suited to maintain a few close relationships. On the other hand, Lightweight methods make it easier for people to have many weak social relationships [11, 12].

People use both social grooming methods depending on the strengths of so-
cial relationships [8] (Fig. S1) caused by these differences. They have different roles. The role of elaborate methods should be to get cooperation from others. Humans tend to cooperate with close friends [15, 16, 14, 26, 13, 22] because cooperators cannot cooperate with everyone [27, 22]. The role of lightweight social grooming should be to get information from others. Weak social relationships tend to provide novel information [9, 10, 11].

Thus, it should be effective for people to use elaborate social grooming to close relationships expecting cooperation from these relationships. They use widely lightweight social grooming to weak relationships expecting novel information. As a result, the number of close relationships before and after SNS has not changed much [13]. Weak relationships after the appearance of SNS have been maintained effectively [8, 4].

An advantage of information would have increased with changes of societies. As a result, lightweight social grooming has been necessary, and humans have had expanded and shallow social structures. Humans probably have gotten this social grooming in the immediate past. This consideration will become clearer by analysing various data-sets, e.g. other non-human primates, social structures in various times and cultures, and other communication systems.
Methods

Data-Sets

We used thirteen diverse data-sets (see table S2 for details): a) Twitter data (used as test set in the paper [3]) recording interactions among 2,585 people with 278,475 relationships, from 23/6/2007 to 17/3/2010, where an act of social grooming was defined as using the “mention” or “reply” functions to communicate with others. We used the number of characters per day as the amount of social grooming $v$; b) and c) Data from the Japanese SNS 755 [4] which provides two types of communication systems data, dating from 1/1/2015 to 31/3/2015, which we treated as two different sets (see Fig. 1 of supplementary information in the paper [4] for specifications), namely data from group chats and that from wall communications. The former data records interactions among 17,796 users with 238,611 relationships, where we defined an act of social grooming as communicating in a chat limited to two members. The latter data records interactions among 20,000 users with 534,475 relationships, where we defined an act of social grooming as posting a comment on another’s wall. We removed data relevant to official users from both data-sets. We used the number of characters per day as the amount of social grooming $v$; d) Data from Japanese avatar chat Ameba Pigg [4] which records interactions among 76,379 users with 1,610,710 relationships, from 1/10/2014 to 31/12/2015 (see Fig. 2 of supplementary information in the paper [4] for specifications), where we defined an act of social grooming as communicating in a chat limited to two members.
We used the number of characters per day as the amount of social grooming; e) Data from mobile phone calls [6] (Mobile phone (dormitory)), recording mobile phone calls among 73 people with 7,805 relationships from 5/9/2008 to 29/6/2009, where we defined an act of social grooming as one call to another. The subjects were undergraduates in a dormitory who probably communicated with unrelated people (the same is true of item f). We used duration per day as the amount of social grooming; f) Data from SMS [6] (SMS (dormitory)), which records SMS among 61 people with 2,266 relationships from 1/1/2008 to 27/6/2009, where we defined an act of social grooming as sending one message to another. We used frequency of messaging per day as the amount of social grooming because we did not consider any information regarding the number of characters in this data-set; g) Data from E-mails and letters [2] (E-mail/Letter (Pachur)), which records E-mail and letter communications among 40 people’s data for 100 days. This data was recorded together with data-sets of item j and k. These data-sets do not have the information of the amount of social grooming; h) Data from mobile phone calls [5] (Mobile phone (friends & family)), recording mobile phone calls among 114 people with 2,264 relationships from 4/5/2010 to 19/11/2010, where we defined an act of social grooming as a call to another. The subjects were members of a young family living in a residential community which was constructed by kin and neighbors (the same is true of item i); i) Data from SMS [5] (SMS (friends & family)), recording mobile phone calls among 109 people with 2,294 relationships from 14/3/2010 to 16/7/2011, where we defined an act of social grooming as a call to another;
j) Data of face to face communication [2] (Face to face (Pachur); see item g for details); k) Data from phone calls [3] (Phone (Pachur); see item g for details); l) and m) Data of social grooming among Chacma baboons in two groups [7] (Baboon group A, B), which records far cleaning behaviour among 35 (B: 24) individuals with 266 (B: 225) relationships in 681 (B: 657) sessions, where the session is a quarter day (before 9 o’clock, 9-12 o’clock, 12-15 o’clock, and after 15 o’clock). We used the session instead of a day because this data-set does not have the date information. We used frequency of far cleaning per session as the amount of social grooming v.

In the data-sets from Twitter, 755 (group chat and wall communication) and Ameba Pigg, we limited the targets of analysis to active users who had greater number of social grooming days than the 50th percentile among Twitter users and the 75th percentile among 755 and Ameba Pigg users because these internet service data-sets included many inactive users. In this paper, we defined the strength of social relationships $d_{ij}$ as the days on which individual i does social grooming to individual j.

**Individual-based Model**

We modeled that social grooming behaviour depends on a constraint of social grooming (trade-off $C_i = N_i m_i^a$). This social grooming behaviour will affect social structures. To explore the effect of trade-off parameter $a$ on social structures, we constructed a simulation model of social grooming under the constraints in the amount of social grooming obeys $G(a, \alpha; C, m)$ (Eq. 1). Social
grooming time on each relationship and each day increases along with social grooming density \( w_{ij} \) (Fig. S4, S5). We used this linear function \( v(w_{ij}) = \alpha w_{ij} + 1 \) as the simplest assumption of this phenomenon [4], where \( v \) is the amount of social grooming from \( i \) to \( j \) on a day and \( w_{ij} \) is social grooming densities \( d_{ij} / t \) (\( t \) is the number of elapsed days). In the model, we considered two type individuals which were groomers and groomees. Groomers construct social relationships using their limited resources \( R \) (that is, time), based on these assumptions and the Yule–Simon process [2, 4] (Fig S3). Section S2 shows a source code of this model.

We conducted the following simulation for \( T \) days to construct social relationships \( d_{ij} \) in experiment 1 and 2. Individuals have a social relationship where strength is 1 as the initial state. At each day \( t \), groumer \( i \) repeats the following for its resource \( R_i > 0 \). \( R_i \) is reset to an initial value \( G(a, \alpha; C_i, m_i) \) before each day \( t \). Each \( i \) spends \( R_i \) during the reinforcing of its social relationships.

Each \( i \) creates social relationships with strangers (groomees). The strength of a new social relationship with \( j \) (\( d_{ij} \)) is 1. The number of new relationships obeys a probability distribution \( \text{Poisson}(p_i) \), where \( p_i \) is \( (N_i - 1) / T \). Therefore, \( i \) is expected that it has \( N_i \) social relationships until day \( T \).

\( i \) also reinforces its social relationships. Each \( i \) selects a social grooming partner \( j \) depending on a probability proportional to the strength of the social relationships between \( i \) and \( j \), then \( i \) adds 1 to \( d_{ij} \) (that is, the Yule-Simon process) and spends the amount of social grooming \( v(w_{ij}) \) from \( R_i \) (if \( R_i < v(w_{ij}) \), then \( i \) adds \( R/v(w_{ij}) \) to \( d_{ij} \) and \( R_i \) becomes 0). Each \( i \) does not perform
the act of social grooming more than once with the same groomees in each day \( t \). Therefore, selected groomees are excluded from the selection process of a social grooming partner \( j \) in each day \( t \).

**Experiment 1**

In this experiment, we confirmed a consistency between \( C = Nm^a \) and two assumptions of social grooming behaviour (\( G(a, \alpha; C_i, m_i) \) and \( v(w_{ij}) = \alpha w_{ij} + 1 \)). Therefore, we fitted our model to the data-sets optimized by unknown parameter \( \alpha \). We used the parameters \( a, T, C_i \), and \( p_i \) where \( a \) were the values in Fig. 2. \( T \) was the period for each data-set, and \( C_i \) was the 75th percentile of \( u^k \), \( N_i \) was given equally divided in a logarithmic scale. Unknown parameter \( \alpha \) was calculated by the optimization which decreased error values of simulations 
\[
\sum_i^M \left( (\log N_i - \log N'_i)^2 + (\log m_i - \log m'_i)^2 \right)/M,
\]
where \( m_i = (C/N_i)^{(1/a)} \), \( M \) was the number of individuals, and \( N'_i \) and \( m'_i \) were calculated by simulation results \( w_{ij} \).

**Experiment 2**

In this experiment, we analysed the effect of parameter \( a \) on the structure of social relationships by using this model. First, we calculated \( e_{aa} \) in each \( a \) and \( \alpha \), where \( a \) is \( \{0.50, 0.55, \ldots, 2.00\} \) and \( \alpha \) is \( \{1.00, 1.02, \ldots, 3.00\} \) (Fig. 4b), where we used \( T, C_i \) and \( N_i \) of the Twitter data-set as in Experiment 1. Each \( e_{aa} \) was calculated fifty times. Next, we calculated social structures \( (d_{ij}) \) in each \( a \) by using actual settings \( (T, C_i, N_i) \) and \( \alpha \), where \( T \) was the period for Twitter.
data-set, $C_i$ was individual $i$'s $u_i^k$, and $N_i$ was $i$'s number of social relationships in Twitter data-set. On evaluating social structures (power law coefficients), we used $\alpha$ which was ranked in the lowest twenty of $e_{aa}$ of each $a$. As a result, we got twenty social structures of each $a$.

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Figure 1: We found two types of social grooming (elaborate social grooming (orange) and lightweight social grooming (green)) and social structures depending on them (Fig. a: conceptual diagram, Fig. b: macro-social structures, Fig. c: constraints to social grooming behaviour, and Fig. d and e: micro-human behaviour depending on these constraints). People and non-human primates tended to do elaborate social grooming (e.g. face to face communication and far cleaning in primates) with close social relationships. This social grooming generated limited and deep societies (the orange line in Fig. b). On the other hand, people tended to do lightweight social grooming (e.g. SNS and E-mail) with weak social relationships. This social grooming generated expanded and shallow societies (the green line in Fig. b). The former may have been used in modern societies with close relationships and non-human primate societies, and near-primitive human societies. The latter seemed to be used in modern societies with weak relationships. These social grooming methods were separated by parameter $a$ of trade-off relationships between the number and the strength of social relationships ($C = Nm^a$). A method of $a < 1$ is elaborate social grooming, and a method of $a > 1$ is lightweight social grooming. The black lines are the threshold ($a = 1$) in these Figs. People changed their social grooming behaviour depending on $a$. The first is the gradients of an amount of social grooming (the gradients of Fig. d) increase with the strength of social relationships. The stronger the social relationships, the greater the amount of social grooming is spent on social grooming in those relationships. The gradients of lightweight social grooming ($a > 1$) were lower than of elaborate social grooming ($a < 1$). The second is the total amount of social grooming of each individual (Fig. e). People having limited and deep social relationships tended to do social grooming frequently when $a < 1$ (the amount of social grooming was large). On the other hand, people having expanded and shallow social relationships tended to do social grooming frequently when $a > 1$. These two different behaviours depending on the trade-off changed social structures (Fig. b). Figs. b-e were drawn by using Twitter data-set ($a = 0.5$: orange, $a = 1.0$: black, $a = 1.5$: green; see Fig. 4 for details).
Figure 2: Two types of social relationships separating by trade-off relationships between \( N \) and \( m \). This figure shows \( \log N / \log C \) and \( \log m / \log C \) to remove the effect of covariate \( C \) from the relationships between \( N \) and \( m \). These were separated by parameter \( a \) on \( C = Nm^a \) model \( \mathbb{H} \) (\( a \) was obtained by fitting the regression model \( \log N \sim \text{Normal}( -a \log m + b \log u, \sigma ) \) to the data-sets; see Table S3 for details). Fig. a-g are lightweight social grooming \((a > 1)\) and Fig. h-m are elaborate social grooming \((a < 1)\). The black points show user behaviour data, orange lines show the regression lines of the models when \( a = 1 \) \((C = Nm)\), and green dash lines show the regression lines of \( C = Nm^a \) models. \( a < 1 \) shows a weak trade-off between \( N \) and \( m \), as a result, people tended to construct a few strong social relationships. On the other hand, \( a > 1 \) shows a strong trade-off between \( N \) and \( m \), as a result, people tended to construct many weak social relationships.
Figure 3: The simulation model fits the data-sets (experiment 1). This shows consistency of the model with two assumptions \(v(w_{ij}) = \alpha w_{ij} + \beta\) and \(G(a, \alpha; C, m)\). The results fit by the simulation model to the regression lines of all data-sets (that is, green and dashed lines in Fig. 2), where these fitting parameters were \(\alpha\). Very good fits were observed between the simulation results (orange triangles) and the regression lines (green lines). \(T\) is the number of days of the data periods and each user use-days \(u\) were 75th percentile \((C = u^{\frac{3}{2}})\). The parameters \(\alpha\) of \(v(w_{ij})\) and \(G(a, \alpha; C, m)\) were \(\alpha = 1.034927\) (Twitter), \(\alpha = 1.20697\) (755 group chat), \(\alpha = 1.131248\) (755 wall communication), \(\alpha = 0.9460449\) (Ameba Pigg), \(\alpha = 2.734375\) (Mobile phone (dormitory)), \(\alpha = 1.019287\) (SMS (dormitory)), \(\alpha = 1.708984\) (E-mail/Letter (Pachur)), \(\alpha = 1.887512\) (Mobile phone (friends & family)), \(\alpha = 1.562500\) (SMS (friends & family)), \(\alpha = 2.148438\) (Face to face (Pachur)), \(\alpha = 1.660156\) (Phone (Pachur)), \(\alpha = 1.044464\) (Baboon group A), and \(\alpha = 1.020813\) (Baboon group B).
Figure 4: A change of skewed social structures (power law coefficients $\phi$ on distributions of social relationship strengths $d_{ij}$) around a threshold $a = 1$ (Fig. a). The black points are the mean of twenty values on each $a$ (see hereinafter) and the error bars are standard deviations of these values. The orange and green lines in Fig. a are the result of the regression of $\phi \sim \text{Normal}(\beta_1 a f + \beta_2 a (1 - f) + \beta_3 f + \beta_0, \sigma)$, where $f = 1$ when $a \geq 1$ else $f = 0$ (see table S4). This model was compared with another model where we did not assume the threshold $a = 1$, i.e. $\phi \sim \text{Normal}(\beta_1 a + \beta_0, \sigma)$. We selected the former model based on AIC. That is, the green line shows the gradient of coefficients $\phi$ in $a \in [0.5, 1.0)$ and the orange line shows the gradient of $\phi$ in $a \in [1.0, 2.0]$. The gradient of $\phi$ when $a > 1$ was larger than when $a < 1$. That is, power law coefficients $\phi$ (expanded and shallowness of social structures) when $a > 1$ tended to change more than when $a < 1$. Simultaneously, $\alpha$ was dramatically decreased when $a < 1$, i.e. individuals decreased social grooming time for strong social relationships (Fig. b). The cell colors in Fig. b show the normalized mean error values of the simulations (the mean of $e_{aa}/\sum_{a \in [1, 3]} e_{aa}$). The white line shows mean $\alpha$ in the lowest twenty $e_{aa}$ in each $a$. The error bars show their standard deviations. These values of the coefficients and $\alpha$ were calculated by the individual-based simulations (see Experiment 2 section in Methods section).
S1 Development of Social Grooming for Reinforcement of Social Relationships

We develop Eq. 1. The strength of social relationships between \(i\) and \(j\) at day \(t\) \((d_{ij}(t))\) increases the amount of social grooming \(v_{ij}(t)\) (Fig. S4). The gradient of this increase depended on a density of social grooming, not frequency (Fig. S5). Thus, \(v_{ij}\) does not depend on \(t\), i.e. \(d_{ij}(t)/t = w_{ij}\)

\(m_i\) is the mean of \(i\)'s strength of social relationships, and \(N_i\) and \(m_i\) are at time \(T\). That is,

\[
m_i = \frac{1}{N_i} \sum_{j=1}^{N_i} d_{ij}(T) = \frac{T}{N_i} \sum_{j=1}^{N_i} w_{ij}. \tag{S1}
\]

Therefore, we acquire

\[
\sum_{j=1}^{N_i} w_{ij} = m_i N_i / T. \tag{S2}
\]

Here, we used a linear social grooming amount function \(v(w_{ij}) = \alpha w_{ij} + 1\) as the simplest assumption. As a result, the total amount of social grooming per day \(V_i\) is as follows.

\[
V_i = \sum_{j} v(w_{ij}) \tag{S3}
\]

\[
= \alpha \sum_{j=1}^{N_i} w_{ij} + N_i \tag{S4}
\]

\[
= \alpha m_i N_i / T + N_i \tag{S5}
\]
Therefore, we acquire a function of the total amount of social grooming per day 
\[ V(a, \alpha; N, m) = \alpha mN/T + N. \]

\( V(a, \alpha; N, m) \) includes reinforcing existing social relationships \( G \) (Eq. 1) and making new social relationships \( G_0 \). We separate them. Consider an individual * who makes a new social relationship every day and does not reinforce their social relationships, i.e. \( C_* = T = N_* \) and \( m_* = 1 \). Thus, *’s \( V(a, \alpha; N_*, m_*)T \) is \( V_0 N_* \), where \( V_0 \) is an amount of social grooming to make a new social relation. This equals \( V(a, \alpha; N_*, m_*)T = (\alpha m_*N_*/T + N_*)T \). Therefore, \( V_0 = \alpha + T \). As a result, we acquire Eq. 11 in the following.

\[
\begin{align*}
G(a, \alpha; C, m) &= \alpha mN/T + N - V_0N/T \\
&= \alpha N(m - 1)/T \\
&= \alpha C(m^{1-a} - m^{-a})/T
\end{align*}
\]

\( G_0 \) is as follows.

\[
\begin{align*}
G_0 &= (\alpha + T)N/T \\
&= N(\alpha/T + 1) \\
&\approx N,
\end{align*}
\]

where we consider sufficiently large \( T \), i.e. \( T >> \alpha \).
S2 Source Code of Individual-based Simulations

The following shows an R source code for individual-based simulations with parameters: “alpha” is $\alpha$, “maxT” is $T$, “L” is the number of groomers, “N” is vector of groomers’ $N$, and “m” is vector of groomers’ $m$. The dimensions of “N” and “m” are “L”. “simulation” function returns each groomer $i$’s strength of social relationships with each $j$ at $T(d_{ij})$.

```r
library(dplyr)

simulation <- function(alpha, maxT, L, N, m){
  G <- alpha * N * (m-1)/maxT

  res <- tbl_df(bind_rows(lapply(1:L, function(i){
    # expectation value of creating new relationships
    q <- (N[i]-1)/maxT
    # init social relationships
    net <- c(1)

    for(t in 1:maxT){
      # create new relationships
      net <- c(net, rep(1, rpois(1, q)))

      cost <- 0
      done <- rep(0, length(net))
      tmp <- net
      while(G[i] >= cost & sum(done) < length(net)){

      }
    }
  }))
```

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tmp <- net
tmp[done != 0] <- 0

p <- cumsum(tmp)/sum(tmp, na.rm=T)
dart <- runif(1, 0, 1)
ind <- min(which(p >= dart))

dcost <- alpha * net[ind]/t + 1

done[ind] <- 1
net[ind] <- net[ind] +
  ifelse(cost + dcost > G[i], (G[i] - cost) / dcost, 1)

cost <- cost + dcost

}

}
data.frame(i=i, w=net)

)}}
res
}
Fig. S1: People tended to use more elaborate social grooming with stronger social relationships. This figure shows the ratio of social grooming methods on each strength of social relationships $d$. This figure was drawn by the author from Pachur et al. data-set [2]. The ratio of the lightweight method (E-mail/Letter) decreased with the increase of $d$. On the other hand, the ratio of the elaborate method (Face to face) increased with $d$. The ratio of Phone showed an intermediate tendency between both.

Fig. S2: Cumulative distributions of the number of days $d_{ij}$ of interaction between individual $i$ and $j$. These results were similar to those of previous studies [28, 23, 29, 30, 4].
Fig. S3: The Yule–Simon process on social grooming strategies. These figures show probability $p$ of social grooming on days after each strength of social relationship $d$. This indicates that the power law distributions were generated by the Yule–Simon process because the $p$ was proportional to $d$, and these strategies subsequently generated the power law distributions. The data periods were from the first thirty days. We did not observe the similar trends in the other data-sets due to insufficient data. However, they seem to obey the same process, because the generated distributions of all data-sets show the same distributions, i.e. power law distributions (Fig. S2). These results were similar in a previous study [2].

Table. S1: High correlations of $\log G(a, \alpha; C_i, m_i)$ and $\log V_i$, where $V_i$ is a summation of $i$’s amount of social grooming per day without initial social grooming with strangers.

| Communication System          | Correlation | p-value          |
|------------------------------|-------------|------------------|
| Twitter                      | 0.8399704   | Less than $2.0 \times 10^{-16}$ |
| 755 group chat               | 0.7057239   | Less than $2.0 \times 10^{-16}$ |
| 755 wall communication        | 0.8130384   | Less than $2.0 \times 10^{-16}$ |
| Ameba Pigg                   | 0.767580    | Less than $2.0 \times 10^{-16}$ |
| Mobile phone (dormitory)     | 0.7434336   | $5.0 \times 10^{-14}$ |
| SMS (dormitory)              | 0.9079204   | Less than $2.0 \times 10^{-16}$ |
| Mobile phone (friends & family) | 0.9749272 | Less than $2.0 \times 10^{-16}$ |
| SMS (friends & family)       | 0.9733798   | Less than $2.0 \times 10^{-16}$ |
| Baboon group A               | 0.9789251   | Less than $2.0 \times 10^{-16}$ |
| Baboon group B               | 0.9790673   | Less than $2.0 \times 10^{-16}$ |
Fig. S4: Increasing amount of social grooming per day $v$ by strengths of social relationships $d$. The definitions of an amount of social grooming are shown in Data-Sets section in Methods section. The orange lines are the 25th percentile, the green and dotted lines are the 50th percentile and the blue and dashed lines are the 75th percentile. These are shown for cases where the number of samples was more than 20 (the ranges of the $d$ of Fig. e-j are short because these were smaller data-sets).

Fig. S5: The gradients of the amount of social grooming depending on social grooming density as distinct from those depending on social grooming frequency. These figures show compaction of the medians of $v$ for each social grooming density ($d/t$) for different periods ($t$ is the number of elapsed days). Each line represents entire periods (orange lines), nine-tenths of the periods (green and dotted lines), and eight-tenths of the periods (blue and dashed lines). These are shown when the number of samples is more than 20 (the ranges of $d$ of Fig. e-j are short because these were smaller data-sets).
Fig. S6: The cumulative distributions of strengths of social relationships $d_{ij}$ of each data-set (black points) and a simulation result of each data-set (orange points). The simulation results roughly show similar trends with each data-set excluding Face to face (Pachur).
Table S2: Summaries of data-sets. N and m were tallied for each individual, d was tallied for each relationship and v was tallied for each combination between relationship and day.

| Communication System | Variable | Size | min | 2.5%ile | 25%ile | 50%ile | 75%ile | 97.5%ile | max |
|----------------------|----------|------|-----|---------|--------|--------|--------|----------|-----|
| Twitter              | N        | 2.585| 7   | 28      | 65     | 94     | 136    | 264      | 736 |
|                      | m        | 2.585| 1.25| 1.84    | 2.79   | 3.55   | 4.66   | 8.61     | 25.23|
|                      | d        | 278.475| 1   | 1       | 1      | 1      | 3      | 20       | 166 |
|                      | v        | 943.719| 2   | 21      | 54     | 94     | 136    | 383      | 14,120|
| 755 group chat       | N        | 17.796| 1   | 1       | 5      | 9      | 17     | 51       | 187 |
|                      | m        | 17.796| 1.00| 1.43    | 2.44   | 3.53   | 5.60   | 18.00    | 112.00|
|                      | d        | 238.611| 1   | 1       | 1      | 2      | 4      | 18       | 112 |
|                      | v        | 901.212| 1   | 1       | 17     | 48     | 143    | 1,072    | 31,990|
| 755 wall communication| N       | 20.000| 1   | 1       | 6      | 11     | 24     | 159      | 1,372|
|                      | m       | 20.000| 1.00| 1.02    | 1.53   | 2.45   | 4.39   | 15.67    | 103.00|
|                      | d       | 534.475| 1   | 1       | 1      | 1      | 2      | 13       | 121 |
|                      | v       | 1,270.546| 3   | 6       | 17     | 33     | 73     | 452      | 17,565|
| Ameba Pigg           | N       | 76.379| 1   | 1       | 7      | 13     | 26     | 86       | 689 |
|                      | m       | 76.379| 1.00| 1.11    | 1.91   | 3.14   | 5.82   | 34.50    | 454.00|
|                      | d       | 1,610.710| 1   | 1       | 1      | 1      | 3      | 25       | 457 |
|                      | v       | 6,515.626| 13  | 146     | 365    | 665    | 1,314  | 4,651    | 87,281|
| Mobile phone (dormitory) | N      | 73   | 2   | 16      | 47     | 94     | 126    | 279      | 688 |
|                      | m      | 73   | 1.81| 2.06    | 3.34   | 3.95   | 4.75   | 7.45     | 8.07 |
|                      | d      | 7.801| 1   | 1       | 1      | 1      | 2      | 32       | 207 |
|                      | v      | 32.728| 0   | 0       | 24     | 60     | 223    | 10,261   | 328,031|
| SMS (dormitory)      | N      | 48   | 1   | 1       | 4      | 11     | 19     | 194      | 283 |
|                      | m      | 48   | 1.00| 1.00    | 1.68   | 2.85   | 4.03   | 11.35    | 30.5 |
|                      | d      | 1,233| 1   | 1       | 1      | 1      | 2      | 30       | 153 |
|                      | v      | 4,942| 1   | 1       | 1      | 1      | 3      | 7        | 168 |
| E-mail/Letter (Pachur) | N      | 39   | 1   | 1       | 5      | 12     | 20     | 59.25    | 64 |
|                      | m      | 39   | 1   | 1.4     | 1.79   | 2.24   | 4.75   | 7.45     | 32.9 |
|                      | d      | 602  | 1   | 1       | 1      | 1      | 2      | 6.98     | 18 |
|                      | v      | 1257 | -   | -       | -      | -      | -      | -        | - |
| Mobile phone (friends & family) | N      | 114  | 1   | 1       | 6      | 13.5   | 29.75  | 63.18    | 76 |
|                      | m      | 114  | 1   | 1.64    | 2.17   | 3      | 5.81   | 7.67     | 6.77 |
|                      | d      | 2,264| 1   | 1       | 1      | 1      | 2      | 20.43    | 88 |
|                      | v      | 6,821| 1   | 1       | 1      | 1      | 2      | 6        | 251 |
| SMS (friends & family)| N      | 109  | 1   | 1       | 6      | 15     | 33     | 59.3     | 113 |
|                      | m      | 109  | 1   | 1.57    | 4.14   | 7.8    | 14.82  | 24.69    | 69.4 |
|                      | d      | 2,294| 1   | 1       | 2      | 5      | 30     | 200      | 809 |
|                      | v      | 16,233| 1  | 1       | 1      | 2      | 3      | 10       | 71 |
| Face to face (Pachur) | N      | 39   | 1   | 1.95    | 41     | 56     | 83     | 125.5    | 131 |
|                      | m      | 39   | 1   | 5.41    | 6.87   | 8.71   | 12.56  | 13.69    | 13.69|
|                      | d      | 2,370| 1   | 1       | 1      | 3      | 40.78  | 100      | -  |
|                      | v      | 17,622| -  | -       | -      | -      | -      | -        | -  |
| Phone (Pachur)       | N      | 40   | 1   | 4.90    | 11.75  | 16     | 24     | 40.08    | 43 |
|                      | m      | 40   | 1.37| 1.59    | 2.42   | 3.97   | 5.44   | 5.95     | 5.95 |
|                      | d      | 733  | 1   | 1       | 1      | 2      | 4      | 15       | 51 |
|                      | v      | 2,565| -   | -       | -      | -      | -      | -        | -  |
| Baboon group A       | N      | 35   | 1   | 1       | 3.5    | 7      | 11     | 17.45    | 20 |
|                      | m      | 35   | 1   | 1.23    | 1.67   | 2.26   | 3.03   | 3.91     | 3.91 |
|                      | d      | 266  | 1   | 1       | 1      | 2      | 8      | 14       | 14 |
|                      | v      | 549  | 1   | 1       | 1      | 1      | 2      | 4        | 8  |
| Baboon group B       | N      | 24   | 1   | 2.15    | 5.75   | 10     | 13     | 16.43    | 17 |
|                      | m      | 24   | 1   | 1.49    | 1.97   | 2.85   | 4.56   | 4.80     | 4.80 |
|                      | d      | 225  | 1   | 1       | 1      | 2      | 3      | 9.4      | 18 |
|                      | v      | 579  | 1   | 1       | 1      | 1      | 2      | 4        | 8  |
Table. S3: The results of the regression analysis in Fig. 2. The t-values and the p-values of $a$ measuring the statistical uncertainty in coefficient $a$ are larger than 1 when $a > 1$ and the statistical uncertainty in coefficient $a$ are smaller than 1 when $a < 1$. The t-values and the p-values of $b$ measuring the statistical uncertainty in coefficient $b$ are not equal to 0. The coefficient $a$ was larger than 1 in lightweight social groomings (Twitter, 755 group chat, 755 wall communication, Ameba Pigg, Mobile phone (dormitory), SMS (dormitory), and E-mail/Letter (Pachur)). On the other hand, the coefficient $a$ was smaller than 1 when $a < 1$. The adjusted R-squared values were 0.990 (Twitter), 0.974 (755 group chat), 0.959 (755 wall communication), 0.997 (Ameba Pigg), 0.994 (Mobile phone (dormitory)), 0.990 (SMS), 0.985 (Baboon group A), 0.991 (Baboon group B), 0.978 (Mobile phone (friends & family)), 0.992 (SMS (friends & family)), 0.990 (Face to face (Pachur)), 0.988 (E-mail/Letter (Pachur)), and 0.997 (Phone (Pachur)).

| Social Grooming Method                  | Coefficient | Estimate  | Standard Error | t-value | p-value       |
|----------------------------------------|-------------|-----------|----------------|---------|---------------|
| Twitter                                | $a$         | 1.18957   | 0.03236        | 51.15   | $4.4 \times 10^{-16}$ |
|                                        | $b$         | 1.00925   | 0.00682        | 192.12  |               |
| 755 Group chat                          | $a$         | 1.21423   | 0.00464        | 46.17   | $2.0 \times 10^{-46}$ |
|                                        | $b$         | 1.26977   | 0.00229        | 553.5   |               |
| 755 Wall communication                  | $a$         | 1.56214   | 0.00625        | 89.94   | $2.0 \times 10^{-46}$ |
|                                        | $b$         | 1.47639   | 0.00277        | 533.2   |               |
| Ameba Pigg                              | $a$         | 1.09541   | 0.00074        | 128.23  | $2.0 \times 10^{-46}$ |
|                                        | $b$         | 1.00935   | 0.00031        | 3487    |               |
| Mobile phone (dormitory)               | $a$         | 1.07332   | 0.15756        | 0.48    | $3.2 \times 10^{-2}$ |
|                                        | $b$         | 1.25628   | 0.04689        | 26.795  |               |
| SMS (dormitory)                        | $a$         | 1.24089   | 0.07715        | 3.08    | $3.5 \times 10^{-4}$ |
|                                        | $b$         | 1.21949   | 0.02995        | 40.72   |               |
| E-mail/Letter (Pachur)                 | $a$         | 1.10884   | 0.17744        | 0.613   |               |
|                                        | $b$         | 1.14310   | 0.04267        | 26.789  |               |
| Mobile phone (friends & family)        | $a$         | 0.93982   | 0.13896        | 0.43    | $3.3 \times 10^{-2}$ |
|                                        | $b$         | 1.23703   | 0.04531        | 27.300  |               |
| SMS (friends & family)                 | $a$         | 0.87749   | 0.05906        | 2.07    | $2.0 \times 10^{-2}$ |
|                                        | $b$         | 1.04883   | 0.02360        | 44.45   |               |
| Face to face (Pachur)                  | $a$         | 0.26334   | 0.18489        | 3.984   | $1.6 \times 10^{-2}$ |
|                                        | $b$         | 1.02148   | 0.08065        | 12.666  | $5.1 \times 10^{-15}$ |
| Phone (Pachur)                         | $a$         | 0.87585   | 0.09219        | 1.35    | $9.3 \times 10^{-2}$ |
|                                        | $b$         | 1.07172   | 0.03087        | 34.717  |               |
| Baboon group A                         | $a$         | 0.95319   | 0.16301        | 0.29    | $3.9 \times 10^{-4}$ |
|                                        | $b$         | 1.17293   | 0.05034        | 23.30   |               |
| Baboon group B                         | $a$         | 0.04714   | 0.13587        | 2.60    | $8.2 \times 10^{-3}$ |
|                                        | $b$         | 1.07354   | 0.04763        | 22.539  |               |

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Table S4: The results of the regression analysis in Fig. 4 ($\phi \sim Normal(\beta_1 af + \beta_2 a(1 - f) + \beta_3 f + \beta_0, \sigma)$, where $f = 1$ when $a \geq 1$ else $f = 0$ and $\sigma$ is standard deviations). These adjusted R-squared values were 0.978.

| Coefficient | Estimate | Standard Error | t-value | p-value |
|-------------|----------|----------------|---------|---------|
| $\beta_1$  | 0.82231  | 0.03647        | 22.547  | Less than 2.0 $\times$ 10$^{-16}$ |
| $\beta_2$  | 0.31626  | 0.03837        | 8.241   | 1.03 $\times$ 10$^{-13}$ |
| $\beta_3$  | -0.25673 | 0.03256        | -7.884  | 1.44 $\times$ 10$^{-14}$ |
| $\beta_0$  | 1.58599  | 0.02695        | 58.839  | Less than 2.0 $\times$ 10$^{-16}$ |