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Who teaches children to forage? Exploring the primacy of child-to-child teaching among Hadza and BaYaka Hunter-Gatherers of Tanzania and Congo

Sheina Lew-Levy[a,*], Stephen M. Kissler[b], Adam H. Boyette[c], Alyssa N. Crittenden[d], Ibrahim A. Mabulla[e], Barry S. Hewlett[f]

[a] Department of Psychology, University of Cambridge, United Kingdom
[b] Queens' College, University of Cambridge, United Kingdom
[c] Department of Human Behavior, Ecology and Culture, Max Planck Institute for Evolutionary Anthropology, Germany
[d] Department of Anthropology, University of Nevada Las Vegas, United States of America
[e] Department of Archeology and Heritage, University of Dar es Salaam, Tanzania
[f] Department of Anthropology, Washington State University, United States of America

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ABSTRACT

Teaching is cross-culturally widespread but few studies have considered children as teachers as well as learners. This is surprising, since forager children spend much of their time playing and foraging in child-only groups, and thus, have access to many potential child teachers. Using the Social Relations Model, we examined the prevalence of child-to-child teaching using focal follow data from 35 Hadza and 38 BaYaka 3- to 18-year-olds. We investigated the effect of age, sex and kinship on the teaching of subsistence skills. We found that child-to-child teaching was more frequent than adult-child teaching. Additionally, children taught more with age, teaching was more likely to occur within same-sex versus opposite-sex dyads, and close kin were more likely to teach than non-kin. The Hadza and BaYaka also showed distinct learning patterns; teaching was more likely to occur between sibling dyads among the Hadza than among the BaYaka, and a multistage learning model where younger children learn from peers, and older children from adults, was evident for the BaYaka, but not for the Hadza. We attribute these differences to subsistence and settlement patterns. These findings highlight the role of children in the intergenerational transmission of subsistence skills.

1. Introduction

Teaching is a ubiquitous process of knowledge transmission in diverse cultural settings (Boyette & Hewlett, 2017a,b; Kline, Boyd, & Henrich, 2013; Maynard, 2002), and has theoretically been tied to the evolution of cumulative culture because it is hypothesized to increase the learning fidelity of hard to acquire information (Castro & Toro, 2014; Fogarty, Strimling, & Laland, 2011). In industrialized societies, where learning in schools is normative, adults are usually perceived to be the primary teachers of children (Rogoff, Matusov, & White, 1996), with child-to-child teaching occurring in some informal settings, such as in the playground (Corsaro & Eder, 1990). And yet, in small-scale societies, where much socialization occurs in the playgroup, child-to-child teaching may be central to knowledge transmission (Boyette & Hewlett, 2017a; Imamura & Akiyama, 2016; Maynard & Tovote, 2009). Here, we investigated child-to-child teaching using focal follow data collected among Hadza and BaYaka hunter-gatherer children from Tanzania and the Republic of Congo respectively. By comparing two foraging societies, we aimed to understand how similarities and differences in the socioecologies of childhood contribute to the cultural diversity in, and evolution of, teaching in humans (Kline, Shamsudheen, & Broesch, 2018). We show that child-to-child teaching is common among the BaYaka and Hadza, but that rates of sibling and peer teaching vary alongside subsistence and settlement patterns.

1.1. Teaching in hunter-gatherers

Various fields of research are interested in examining the prevalence and development of teaching across species and cultures. Ethologists investigating teaching in non-human animals view teaching as the modification of behavior in the presence of a naïve learner in order to facilitate the learner's knowledge acquisition, which should come at a

* Corresponding author.
E-mail address: sheinalewlevy@gmail.com (S. Lew-Levy).

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cost to the teacher (Byrne & Rapaport, 2011; Caro & Hauser, 1992). Culture-based definitions, often used to compare western-style school-based education with traditional knowledge systems, define teaching as "student-centred, developmentally appropriate instruction by dedicated adults" (Lancy, 2010, p. 97). Finally, psychologists primarily focus on the complex of specialized cognitive resources that underpin teaching, and view teaching as the deliberate transmission of opaque but generalizable information from knowledgeable to naïve individuals (e.g. Gergely & Csibra, 2006).

Each of these definitions has its strengths and weaknesses. Ethological definitions are advantageous because they focus on behaviors and not mental mechanisms, thus facilitating the study of teaching in non-human species (Kline, 2015). However, assessing the cost of teaching is often difficult to operationalize, and does not rule out the possibility that species-specific teaching evolved as a by-product of other cooperative behaviors (Hoppitt et al., 2008). Psychological definitions of teaching shed light on uniquely human forms of teaching, such as joint attention (Gergely & Csibra, 2006). However, psychological studies on teaching are primarily conducted with western participants, and thus, overlook cross-cultural variation in teaching. For example, Tomasello's (1999) operationalized definition views 'instructed learning' as necessarily occurring from adults to children, while 'collaborative learning' involves peers. This definition systematically excludes children from taking the position of teacher, which may be more prevent in small-scale societies (see Strauss, Ziv, & Stein, 2002 for exception). Finally, culture-based definitions have helped anthropologists challenge the universality of western-style classroom teaching (Rogoff, 2014), but systematically exclude teaching which occurs in the context of everyday activities, including between children (Kline, 2016).

Because of these different definitions, research on the prevalence of teaching in hunter-gatherer (or forager) societies has found contradictory results. On the one hand, ethnographers employing culture-based definitions argue that teaching is rare in foragers because it violates the foundational schemas—or "cultural values and ways of thinking and feeling that pervade several domains of life" (Hewlett, Fouts, Boyette, & Hewlett, 2011, p. 1171)—shared by many foragers, including an ethos of egalitarianism (Woodburn, 1982) and respect for autonomy (Gardner, 1991). For example, Naveh (2016) argued that Nayaka foragers value first-hand knowledge obtained autonomously more than knowledge acquired through teaching (see also Christian & Gardner, 1977). On the other hand, studies using ethological definitions find that teaching does occur among foragers (see Boyette & Hewlett, 2017b; Garfield, Garfield, & Hewlett, 2016; Lew-Levy, Reckin, Lavi, Cristóbal-Azkarate, & Ellis-Davies, 2017 for review). For example, in the only observational study of teaching in hunter-gatherers which included children in early childhood, middle childhood, and adolescence, Boyette and Hewlett (2017a) found that most teaching of children among the Aka was in the domain of ecological knowledge, that children were less likely to be taught as they aged, and that child-to-child teaching was as frequent as adult-child teaching. Few studies have examined teaching in hunter-gatherers from a cognitive standpoint.

Because this paper is primarily concerned with examining the role of children as teachers, we followed Hewlett and Roulette (2016) and others (Boyette & Hewlett, 2017b; Garfield et al., 2016; Hewlett et al., 2011; Kline, 2015) in employing a definition for teaching derived from ethological studies. Specifically, we view teaching as (1) a teacher modifying their behavior to enhance learning in another individual, (2) not the by-product of another activity, and (3) involving sensitivity between the teacher and learner. This definition allows us to consider several types of teaching outlined by Kline (2015, 2016); in *opportunity provisioning,* the teacher provides the learner with the opportunity to attend to stimuli that would otherwise be too difficult or dangerous for the learner to explore independently, such as in task assignment. In teaching by *evaluation*, the teacher provides positive or negative reinforcement of the learner's behavior. In teaching by *enhancement,* the teacher directs a learner's attention towards a social or physical stimulus, such as through demonstration. Finally, in *direct active teaching,* the teacher makes relevant aspects of the stimulus accessible.

While the definition employed in the present paper is closest to that of ethologists, it deviates in one important way; we do not measure the cost of teaching. However, we follow Kline in assuming that some forms of teaching are more costly than others (see Kline, 2015, 2016 for review). One strength of this definition is that it has been employed in several observational studies of teaching in small-scale societies (e.g. Boyette & Hewlett, 2017a; Kline, 2016), thus facilitating cross-cultural comparison. In this paper, we focus on teaching in the domain of subsistence skills due to their primacy in everyday life, their relative difficulty, and their evolutionary significance—making it likely that teaching will be observed in this domain (Hewlett & Roulette, 2016; Kaplan, Hill, Lancaster, & Hurtado, 2000; Kline et al., 2013; Marlowe, 2005). We further examine the prevalence of teaching throughout childhood, which we define as spanning early childhood (aged approx. 3–6) middle childhood (aged approx. 7–12) and adolescents (aged approx. 13–18). We refer to these age groups collectively as 'children'. In what follows, we review the available psychological, anthropological and evolutionary literature in order to develop predictions regarding child-to-child teaching in the domain of subsistence skills.

1.2. Who teaches whom?

Children's teaching capabilities seem to increase throughout childhood (Boyette & Hewlett, 2017a; Maynard & Tovote, 2009; Strauss & Ziv, 2012). Furthermore, children may be especially skilled at teaching other children because they are closer in development, and thus, have privileged knowledge of another child's "Zone of Proximal Development", defined as the distance between what a child can accomplish on their own and what a child can accomplish with help (Vygotsky, 1978). Considering this, Reyes-García, Gallois, and Demps (2016) proposed a multistage learning model for understanding cultural transmission across the life course, with infants learning from parents, young children learning basic competencies from friends, and older children updating this knowledge by learning from preferred models later in life. In support of the multistage learning model, child-to-child transmission has been found to occur in forager playgroups in early and middle childhood (Boyette, 2016; Crittenden, 2016; Konner, 2005), while forager adolescents in some societies, such as the Aka and Chabu, travel relatively long distances to learn complex tasks such as hunting and basketry design from expert adults (Dira & Hewlett, 2016; Hewlett, 2013, 2016; Hewlett & Hewlett, 2012). In addition, simulation studies investigating the optimal learning schedule for the development of cumulative culture suggest that individuals should learn socially (e.g. through teaching, imitation, and play) before they learn individually (e.g. through trial-and-error) (Lehmann, Wakano, & Aoki, 2013). Although certain domains of knowledge such as large game hunting are acquired later in life (Dira & Hewlett, 2016; Walker, Hill, Kaplan, & McMillan, 2002), the overall frequency of social learning should decline with age. Considering these factors, the present study investigated the distribution of teaching throughout childhood.

Furthermore, if teaching is a cooperative behavior (Thornton & Raihani, 2008), then inclusive fitness theory holds that the cost of teaching is more likely to be incurred by closely related individuals (Hamilton, 1964). Theorists have usually assumed that, in early life, teachers should be parents, since parents are more likely to be proximal, closely related to, and presumably more knowledgeable than, their children (Shennan & Steele, 1999). However, McElreath and Strimling (2008) demonstrated that parent-child transmission is more likely to occur in domains that affect fertility, such as childcare, rather than survival, and thus parents might be less concerned with teaching subsistence skills to their children. Since siblings are as related to each other as they are to their parents, have fewer constraints on their time, and since older siblings are likely to know more than their younger

siblings, it may be that siblings are better able to distribute the cost of teaching among themselves. Furthermore, a child can only ever have two genetic parents, but having more than two siblings is normative in most forager societies (Hewlett, 1991; Morelli, Henry, & Foerster, 2014). This may confer an additional advantage to sibling teaching; the sibling dilution hypothesis posits that parental resources are finite, and thus, the more offspring they have, the fewer resources can be allocated to each child (Blake, 1981). This hypothesis has been used to explain the negative effect of number of siblings on height (Bronte-Tinkew & DeJong, 2004) and nutritional status (Kucera & McIntosh, 1991). While forager children are also in competition with each other for resources provisioned by parents, they can reduce their reliance on this provisioning by foraging themselves (Crittenden, Conklin-Brittain, Zes, Schoeninger, & Marlowe, 2013; Hagino & Yamauchi, 2016). Thus, if older siblings teach younger siblings to forage, they may increase their own potential share of parental resources. Evidence for the prevalence of sibling teaching was found among the Maya (Maynard, 2002; Maynard & Tovote, 2009; Zarger, 2002), Aka, and Ngandu (Boyette & Hewlett, 2017a). Taking subsistence skills as its focal point, the present study investigated the kinship relationship between teachers and learners, including siblings.

Next, reciprocity permeates much of forager life, as has been documented in food sharing (Allen-Arave, Gurven, & Hill, 2008; Crittenden & Zes, 2015; Hewlett, 2008; Peterson, 1993) and childcare (Ivey, 2000). An extensive study of BaYaka and Agta foragers (Migliano et al., 2017; Salali et al., 2016) suggested that reciprocal knowledge sharing between friends may improve the efficiency of hunter-gatherer networks, thus facilitating the evolution of cumulative culture. These findings may be supported by several psychological studies which show that by learning collaboratively, children come to learn new aspects of the task at hand, aspects unknown to either previously (Tomasello, 1999; Tomasello, Kruger, & Ratner, 1993). Since collaboration may often involve reciprocity in knowledge exchange, this paper examined whether teaching occured reciprocally in two forager societies.

Finally, previous ethnographic studies suggest that, due to the division of labor within most small-scale societies, including foragers (Brown, 1970; Marlowe, 2007), children are more likely to learn from same-sex than opposite-sex individuals. Cross-culturally, this prediction seems to hold true (Gallois, Lubbers, Hewlett, & Reyes-García, 2018; Hewlett & Cavalli-Sforza, 1986; MacDonald, 2007a; Maynard & Tovote, 2009; Montgomery, 2009) and is hypothesized to facilitate the transmission of sex-relevant skills (Henrich & Gil-White, 2001). Thus, this study investigated the prevalence of teaching in same-sex vs. opposite-sex dyads.

2. Study sites

The literature reviewed above outlined how child-to-child teaching may occur generally. Here, we describe the ethnographic setting for our research. Both the Hadza and BaYaka[1] share the foundational schemas of autonomy, egalitarianism, and sharing; individuals rarely coerce each other or impose their will on one another (Gardner, 1991), age hierarchy is limited, formal leaders do not exist, there are few status differences based on sex (Woodburn, 1982), food and childcare are shared widely outside of the nuclear household (Hewlett et al., 2011; Woodburn, 1982) and food storage is rare (Kelly, 1995). While a lack of previous studies limited our ability to derive meaningful predictions regarding cross-cultural differences in teaching, the present study considers differences in forager subsistence practices as a potential source of variation. We outline these differences in what follows.

[1] The subgroup of BaYaka surveyed in the present research have also been called Mbendjele BaYaka (Lewis, 2008).

2.1. Settlement patterns

The Hadza and the BaYaka inhabit markedly different ecologies; average annual rainfall and daily temperature in Northern Tanzania around Lake Eyasi are 500 mm and 35 °C respectively vs. 1700 mm and 24.5 °C in the Congo Basin (Blurton Jones, 2016; Marlowe, 2010; Thomas & Bahuchet, 1991). Primary Biomass is approximately 11.3 kg/m^2 in Hadzaland vs. 25.4 kg/m^2 in the Congo Basin (Kelly, 1995). Both Hadza and BaYaka camps can fluctuate from 20 to 100 inhabitants according to the distribution of seasonal resources (Bahuchet, 1988; Blurton Jones, 2016; Kitanishi, 1995; Marlowe, 2010; O'Connell, Hawkes, & Blurton Jones, 1991). Nonetheless, ecological differences have consequences for the settlement structure of camps in both populations; Hadza camp areas are much larger than BaYaka camp areas, at 795 m^2 compared to 262 m^2 (Hewlett, Hudson, Boyette, & Fouts, 2019; O'Connell et al., 1991). Furthermore, the mean area per person in camp is 19.2 m^2 for the Hadza, and 11.5 m^2 for the BaYaka. Nearest neighbor data suggests that Hadza houses are usually 5.9 m apart on average, while BaYaka houses are usually 4.9 m apart on average (Hewlett et al., 2019; O'Connell et al., 1991). Put simply, Hadza camps can be larger and more spread out—though they are not always so (Marlowe, 2010; Woodburn, 1968)—partially due to variation in natural environment (Whitelaw, 1991), and because of differing patterns of cooperation and sharing (Hewlett et al., 2019). Functionally, this means that Hadza children are more likely to assort with members of their nuclear families than BaYaka families. The present study thus considered whether differences in settlement structure between Hadza and BaYaka camps influenced the frequency of sibling and parental teaching.

2.2. Subsistence activities

Though both the Hadza and BaYaka hunt and gather for subsistence, the resources they target, and the tools they use to target these resources, differ. The Hadza collect baobab, tubers, fruit, honey, and eggs, and hunt small game and birds as well as medium to large game animals with bows and arrows (Blurton Jones & Marlowe, 2002; Crittenden et al., 2013; Marlowe, 2010). In addition, the Hadza consume some maize and other domesticated grains provided by local missionaries, tourist companies, or purchased/traded from neighboring pastoralists (Blurton Jones, 2016; Crittenden et al., 2017; Pollom, Herlosky, Mabulla, & Crittenden, Under review). The BaYaka forage for tubers, nuts, mushrooms, caterpillars, insect grub, and liana fruit (Kitanishi, 1995). The BaYaka also fish with poison, hook-and-line, and by bail fishing, and trap and hunt small and large animals with snares, spears and guns. Though the BaYaka are far less mobile today than reported in earlier texts (Bahuchet, 1990; Lewis, 2002), the families with whom we worked still frequently lived in the forest for months at a time, including during honey season, caterpillar season, pepper season, bail fishing season, and periodically while hunting with guns belonging to their farmer neighbors, with whom they maintain extensive trade relations (Joiris, 2003). Finally, the BaYaka keep small gardens where they cultivate bananas, cassava, and maize.

It has been widely reported that Hadza children participate in foraging from an early age; for example, Blurton Jones, Hawkes, & Draper (1994) and Hawkes, O'Connell, & Blurton Jones (1995) showed that children above the age of five collected up to 50% of their daily energy requirements. More recently, Crittenden et al. (2013) found that Hadza children as young as six produced between 25 and 100% of their daily energetic requirements, depending on sex, age, individual motivation, and the type of resource being targeted. Both sets of studies noted that children primarily focus their foraging efforts on baobab, berries, small game, and birds. Parents encourage children's participation in foraging by making small digging sticks for girls and small bows and arrows for boys, which are used to hunt mice and birds around camp (Crittenden et al., 2013). BaYaka children's foraging returns, on

the other hand, are small (Hagino & Yamauchi, 2016). Our previous research also shows that BaYaka children participated in less foraging than their Hadza counterparts (Lew-Levy et al., 2019). While BaYaka parents also make small tools for their children, these tools are less frequently used for subsistence activities. The present study thus considered whether differences in children's participation in foraging influenced knowledge acquisition through teaching.

3. Predictions

Considering the literature reviewed above, we used focal follow data collected among BaYaka and Hadza forager 3- to 18-year-olds to test the following predictions regarding the teaching of subsistence skills to children: (1) The frequency of teaching by children is positively associated with age; (2) the frequency by which children receive teaching is inversely associated with age; (3) consistent with a multistage model of knowledge acquisition, younger children are more likely to be taught by other children while adolescents are more likely to be taught by adults; (4) overall, teaching is more likely to occur between more closely related individuals; (5) teaching will be more likely within same-sex dyads; and (6) teaching will be reciprocal. Additionally, we considered settlement structure and participation in foraging as potential sources for cross-cultural variation in teaching among the Hadza and BaYaka.

4. Methods and analyses

4.1. Data collection

Behavioral data were collected among the Hadza of Tanzania in March and April 2017 and among the BaYaka of Congo in August through September 2017 by SLL. Data collection for both the Hadza and BaYaka took place in seasons when children were particularly productive: for the Hadza, data collection straddled honey and berry seasons (Marlowe & Berbesque, 2009) while for the BaYaka, data collection straddled bail fishing and caterpillar seasons (Bahuchet, 1988; Kitanishi, 1995). Both children and adults participate in these activities, often together. Access to schools is sporadic in both Hadza and BaYaka communities surveyed, and none of the children sampled attended school at the time of data collection. Furthermore, because children's autonomy is respected, when formal schools are available, children choose whether or not to attend independently from adult interreference. However, most BaYaka children in our sample had spent at least a few months in school prior to data collection, and children in one of the three Hadza camps lived near a school, with a handful of children attending daily.

A subset of 35 Hadza children (M_{age} = 10.06, SD = 3.93, 40% female) and 38 BaYaka children (M_{age} = 10.53, SD = 4.16, 39% female) between approx. 3 and 18 years of age were followed. All adolescents in our sample were unwed, had no children, and were identified as youth by community members. BaYaka children were sampled from 5 camps that ranged from 7 to 43 inhabitants (M = 23.00, SD = 15.05), and Hadza children were sampled from 3 camps that ranged from 41 to 73 inhabitants (M = 53.67, SD = 17.01). Because few of the Hadza and BaYaka in our sample knew their ages in years, we followed Crittenden et al. (2013) and others by ranking individuals within the camp—allowing for ties—from oldest to youngest, either within a nuclear family or within a set of closely related cousins. Based on this ranking system, the research team estimated their age. For individuals under 20, estimates were made at 1-year intervals. Because adult age was more difficult to estimate, it was estimated at ten-year intervals starting from 25 onwards.

In order to understand camp demographics, a full census of camp members was conducted upon our arrival. This list was modified during our stay to reflect only individuals whom, at the time of data collection, were permanent camp residents. Based on this census, kinship was inferred by conducting genealogical interviews in each camp, both upon arrival in a camp and prior to departure, as well as informally throughout our stay, in order to obtain the clearest possible picture of kin relations.

Observations of teaching were systematically recorded using a focal follow procedure (Altmann, 1974). Each child was observed for two 2-hour time blocks over a randomly assigned single day, scheduled once in the morning (usually between 8 and 11 am) and once in the afternoon (usually between 12 and 3 pm) using a 30-second observe/30-second record procedure. In cases of especially bad weather or community events in which the researcher could not participate, observation blocks were paused or postponed, and resumed as soon as possible, usually the same day. Follows occurred both in and outside of camp, and were conducted with a field assistant who translated any interactions (either in participants' first language or their second language—Hadzane and Swahili for the Hadza, BaYaka or Lingala for the BaYaka) which occurred between the focal child and other individuals inhabiting the camp. SLL and the assistant stayed close to the focal child for approximately 1 h prior to the start of the follow, in order to habituate the child to their presence, and avoid the child leaving camp without them. If the child showed obvious signs of nervousness or fear prior to the start of the follow, or if the child grew uncomfortable or distracted by the presence of researchers during the follow, the follow was stopped. If a child was not available during the assigned day, that child was rescheduled or omitted. On average, children were observed for 218.81 (SD = 39.32) minutes, totalling 15,973 observations.

The specific teaching behaviors coded during observations were modelled after similar coding schemes (Boyette & Hewlett, 2017a; Childs & Greenfield, 1980; Kline, 2015, 2016; Maynard, 2002) and are described in Table S1. The first teaching event which occurred in the 30-second-observation window was recorded. We also recorded the direction of the teaching event (i.e. to or from the focal child), and the names of up to two individuals with whom the teaching event occurred. Seven percent of teaching observations for the Hadza and 3% of teaching observations for the BaYaka included multiple individuals; these were counted as separate teaching events in the analysis.

The analyses presented here are based only on overall teaching and not separated according to teaching type (instruction, demonstration, etc.) for two reasons; first, each teaching type occurred too infrequently to be modelled independently with the present modelling framework, and, second, analyzing teaching by type can potentially obscure broader trends in teaching. We also only included teaching events which were in the domain of subsistence skills, such as “food procurement, preparation, and cultivation, as well as the procurement and use of plants for the construction of houses, household items, and crafts” which are necessary to survival (tools, containers, etc.) (Zarger, 2002, p. 2). The observed frequency for each category of behavior identified as teaching for subsistence skills, and the frequency of teaching observed for each type of subsistence skill are in Tables S2-S3.

4.2. Inter-coder reliability

We validated the coding scheme by collecting inter-coder reliability data between June and July 2017 among BaYaka children living in a village setting. The Congo research team (SLL and AHB) simultaneously followed 7 focal children for a total of 711 observations. Qualitative reliability assessments were conducted after each follow, and SLL and AHB reviewed any disagreements in order to improve reliability for subsequent follows. The calculation of Cohen's Kappa was only conducted after all reliability data was collected. Reliability was high across all codes; teaching (yes/no) (K = 0.92, SE = 0.03), direction (to/from) (K = 0.92, SE = 0.03), type of teaching (K = 0.88, SE = 0.04), and whom to/from teaching occurred (K = 0.84, SE = 0.04).

Table 1
Variable names, descriptions, and summary statistics for participants in the present study. Each participant alternatively appears as both a teacher and learner in the model.

Variable	Description	N	Mean	SD	N	Mean	SD
Individual-level variables		BaYaka			Hadza		
Sex	Dummy variable to denote that the individual is male	95	0.53	0.50	161	0.54	0.50
Age	Age in years	95	22.41	18.79	161	23.00	19.20
Relationship-level variables							
Parent	Dummy variable to denote parent-offspring ties, r = 0.5	939	0.06	0.23	1894	0.02	0.15
Sibling	Dummy variable to denote sibling ties, $r = 0.5$	939	0.05	0.23	1894	0.03	0.18
Other Kin	Dummy variable to denote other kinship ties, $0.125 \leq r < 0.5$	939	0.11	0.32	1894	0.14	0.35
Same-Sex	Dummy variable to denote that the teacher and learner are of the same-sex	939	0.50	0.50	1894	0.53	0.50

Notes: 15 BaYaka individuals inhabited two separate camps during data collection; 1 BaYaka individual inhabited three separate camps; and 1 BaYaka individual inhabited 4 separate camps. These individuals are included as inhabitants in each camp, leading to repeated observations for these individuals, as well as repeated observations for 9 BaYaka dyads.

4.3. Statistical analysis

These data were analyzed using the Social Relations Model (SRM) developed by Kenny and colleagues (Back & Kenny, 2010; Kenny & La Voie, 1984). A type of social network analysis, SRM facilitates the modelling of directed dyadic interactions. The basic premise of SRM is that interpersonal interactions are necessarily dyadic and involve three components; the general effect of the actor (such as the sharer, speaker, perceiver, or, in our case, the teacher), the general effect of the partner (such as the receiver, listener, perceived, or learner), and finally, the specific effect of the actor-partner relationship. Using sharing as an example, consider that Individual A shares frequently with Individual B. There are three potentially reasons for this: Individual A is very generous and shares with all individuals within the network; Individual B is well liked, and thus, many individuals within the network share with them; or, Individuals A and B are close friends, and thus, Individual A frequently shares specifically with Individual B. The same effects can be decomposed with regards to Individual B sharing with Individual A, and, more generally, any sharing which occurs within a network. Each of these effects—that of the actor, partner, and relationship—are measured as random effects within SRMs in order to understand the contribution of each to overall variance.

SRMs also use correlated random effects to measure two types of reciprocity; generalized and dyadic. Generalized reciprocity can be understood as the degree to which an individual's behavior of interest (sharing, perception, friendship, etc.) is correlated with how others behave towards them. For example, if Individual A shares widely, and many actors within the network also share with Individual A, then generalized reciprocity would be high. Dyadic reciprocity measures the degree to which a behavior is reciprocated within a dyad. For example, if Individual A frequently shares with Individual B, and Individual B frequently shares with Individual A, then dyadic reciprocity would also be high.

Finally, SRMs accommodate external variables, or covariates, for behavior. Each of these covariates can be related to the effect of the actor, partner, or the relationship. For example, if investigating the effect of sex on sharing behaviors, actor sex, partner sex, and whether the actor and partner are of the same sex can be included in the model to uncover whether males or females are more generous, whether males or females are more likely to be recipients of sharing, and whether individuals are more likely to share with members of the same- or opposite-sex.

SRMs have been used in multiple psychological and anthropological studies to understand human behaviors such as status (Anderson & Kilduff, 2009), friendship (Back, Schmukle, & Egloff, 2008), and sharing (Koster & Leckie, 2014; Koster, Leckie, Miller, & Hames, 2015). SRMs are more appropriate than conventional social network analysis techniques for data which are continuous, directed, and potentially incomplete (Van Duijn & Vermunt, 2006). Here, we apply SRM to counts of directed teaching within child-child and child-adult dyads. Each individual within a dyad is represented twice—once in the position of teacher, and once in the position of learner. By considering the teacher as the actor, the learner as the partner, and the teacher-learner dyad as the relationship, we can examine the degree to which each component contributes to the overall variance in teaching. For example, if the variance attributed to the teacher is large, certain individuals within the network may be considered designated teachers. If the variance attributed to the learner is large, many individuals within the network may direct their teaching to a small number of pupils. If the variance attributed to the dyad is large, then individuals may have preferred teaching partners. Finally, in order to account for the hierarchical nature of our data, we included an additional random effect for camp.

We also examine dyadic reciprocity. If dyadic reciprocity is positive, individuals who tend to teach specific alters more than others tend to be taught more by those same individuals. Thus, dyadic reciprocity is a proxy for reciprocal teaching at the level of the dyads. Because we expected that teaching among foragers would be reciprocal, we hypothesized that this value would be positive. Should teaching be unidirectional, this value would be negative. While we did measure generalized reciprocity, we do not interpret it here.

Because not all participants were observed, and because observation periods varied, we use as an offset the log of the total number of observations available for each individual within the dyad. This effectively transforms the outcome count variable into a proportion of observations in which directed teaching has occurred within a dyad (Long & Freese, 2006).

Finally, we included several fixed and interaction effects which represent teacher attributes, learner attributes, and relationship attributes (Table 1);

4.3.1. Age

In order to examine the effect of age on teaching and being taught, we included the age of teacher and age of learner in the model. We z-score standardized these variables in order to facilitate estimations and to facilitate interpretation (Koster & McElreath, 2017; McElreath, 2015). We included both the linear and quadratic effects of age of teacher and age of learner to account for the possibility that this relationship might be U-shaped. In order to test whether child-to-child teaching was more likely to occur when children were younger and adult-child teaching was more likely to occur when children were older, we included the two-way interactions between teacher's and learner's linear age, and teacher's and learner's quadratic age.

4.3.2. Kinship

In order to determine whether kinship relationship predicted teaching, the main effect of kinship relation was included in the model. The coefficient of relatedness (r) was calculated using the

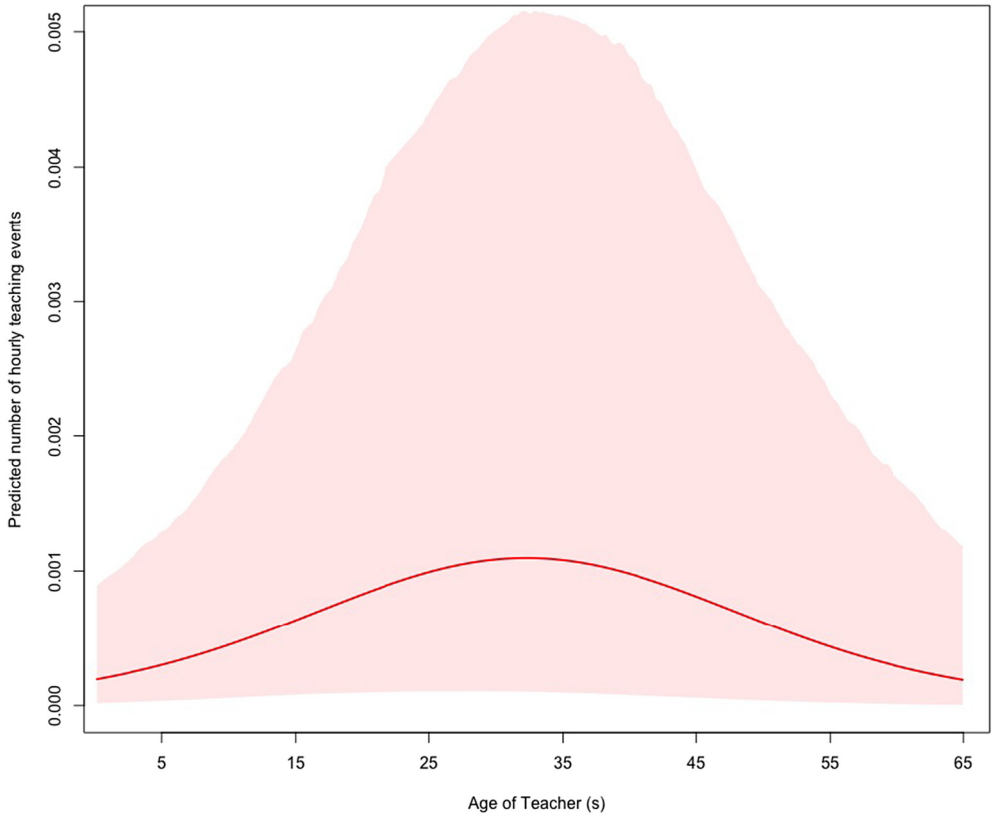

Fig. 1. Model predictions showing the quadratic effect of teacher's age on teaching. Other predictions are held constant at their mean or reference value. Shaded areas depict the 95th percentile credible intervals around the model predictions. Predictions are for 1 h.

aforementioned genealogical data with the R package *kinship2* (Therneau, Atkinson, Sinnwell, Schaid, & McDonnell, 2015). In order to compare sibling and parent-child teaching, we transformed these coefficients into dummy categories; parent-offspring ties ($r = 0.5$), sibling ties ($r = 0.5$), and other kinship ties ($0.125 \leq r < 0.5$). The omitted reference category was non-kin ties ($r < 0.125$).

4.3.3. Sex

In order to determine whether individuals were more likely to be taught by others of the same sex, the binary relationship variable 'same-sex' was considered true if both the teacher and learner had the same sex, and false otherwise. Teacher and learner sex were also included in the model as control variables and were considered to be true if male.

4.3.4. Ethnicity

In order to examine cross-cultural differences in teaching, we included a binary variable for ethnicity in the model. Ethnicity was considered true if an individual was BaYaka, and false otherwise.

4.3.5. Cross-cultural difference

The interaction between ethnicity and all of the above variables were included to investigate differences in Hadza and BaYaka teaching patterns. Specifically, we included two-way interactions for ethnicity and age variables, ethnicity and kinship categories, and ethnicity and sex variables. We also included the three-way interaction term for ethnicity, age of teacher, and age of learner in order to determine whether the age-specific relationship between teacher and learner differed for the Hadza and BaYaka. Following Koster (2018), model predictions were generated for younger children (set at 5 years) and older children (set at 15 years) in each ethnicity in order to interpret these effects.

The parameter values for the SRM was fit using Hamiltonian Monte Carlo estimation, implemented in *RStan* and *rethinking* (McElreath, 2015; Stan Development Team, 2016). We specified flat priors for the fixed parameters in the model. We ran the model on four chains of 2000 iterations each, half of which were warmup iterations. We assessed convergence through the R-hat Gelman and Rubin convergence diagnostic (McElreath, 2015). All R-hat values were smaller than 1.01, and there were no divergent iterations, suggesting good mixing across all models. We report the means, standard deviations, and 95% credible intervals for the parameters. The model formulation is presented in the supplementary materials alongside details regarding model checking and comparison.

5. Results

When considering only unique cases, 14% of Hadza children's observational time and 11% of BaYaka children's observational time was spent teaching or being taught subsistence skills. Hadza children spent 43% of their observation time in camp, and 40% of teaching occurred in this setting. Nineteen percent of Hadza children's time was allocated to active subsistence work, including household activities, and 26% of all Hadza teaching occurred while children were engaged in these activities. BaYaka children spent 57% of their observation time in camp, and 58% of teaching occurred in this setting. Twenty-four percent of BaYaka children's time was allocated to active subsistence work, and 28% of all BaYaka teaching occurred while children were engaged in these activities. Hadza and BaYaka children were in sight or visual range of adults in 57% and 69% of observations respectively. And yet, only 25% of teaching of subsistence skills occurred between adults and children (Hadza; 23%, BaYaka; 27%). Taken together, these data show that while the teaching of subsistence skills did not preferentially occur in a specific location, or during subsistence activities, teaching primarily took place between children, even though children were in visual/speaking range of adults for more than half of their observation periods.

Although our model showed several variables for which the credible

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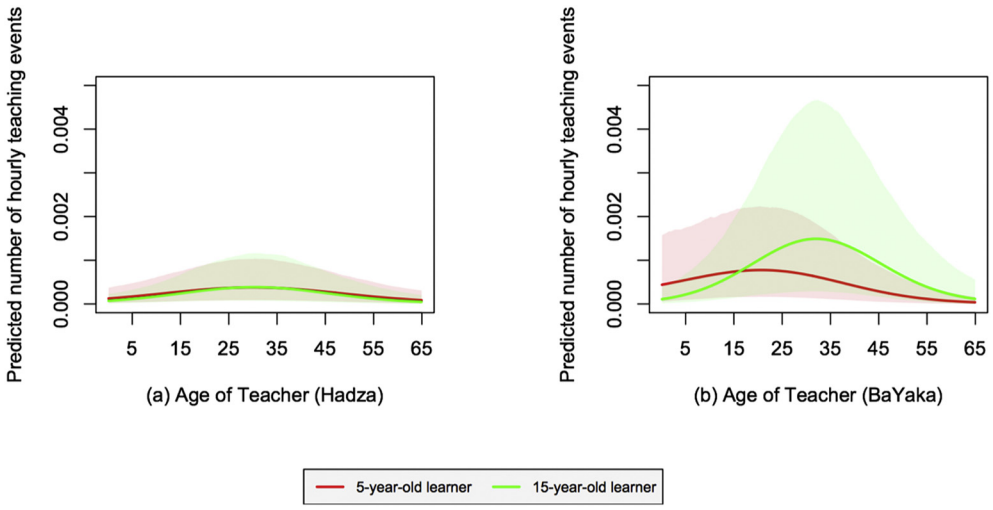

Fig. 2. Model predictions showing the interaction between ethnicity, age of teacher, and age of learner. For younger and older children, predictions are based on children aged 5 and 15 years respectively. Other predictions are held constant at their mean or reference value. Shaded areas depict the 95th percentile credible intervals around the model predictions. Predictions are for 1 h.

intervals do not cross zero, the figures presented below show that these credible intervals are wide, likely due to the fact that data were sparse, so we report our findings with the caveat that they should be interpreted cautiously. Full results can be found in Table S4.

5.1. Age

In support of prediction 1, there was a strong and negative association between the quadratic effect of teacher's age, and the frequency of teaching ($\beta = -0.45$), suggesting that the relationship between the age of teacher and the frequency of teaching followed an inverted-U curve. Fig. 1 shows that teaching increased throughout childhood and young adulthood, peaking around 30 years of age, after which it decreased. We found limited support for prediction 2, as there was only a weak relationship between learner's age and teaching. In partial support of prediction 3, the three-way interaction between ethnicity, teacher's age, and learner's age was a strong predictor for teaching ($\beta = 2.10$). Fig. 2 plots this relationship, suggesting that, for the BaYaka only, younger children were more likely to be taught by other children while older children were more likely to be taught by adults.

5.2. Kinship

For the Hadza, parent-child dyads ($\beta = 3.04$), sibling dyads ($\beta = 3.93$), and other-kin dyads ($\beta = 1.92$) were more likely to experience teaching than non-kin dyads. To identify differences in teaching tendencies between kinship levels among the BaYaka, we calculated contrasts, i.e. posterior estimates of the effect of kinship differences on the expected number of teaching events (McElreath, 2015). Contrasts revealed that BaYaka parent-child dyads (contrast = 3.57), sibling dyads (contrast = 2.22), and other-kin dyads (contrast = 2.04) were also more likely to experience teaching than non-kin dyads (Table S5). Thus, in support of prediction 4, our results showed that, in both ethnic groups, related dyads were more likely than unrelated dyads to exchange teaching. We also found a strong relationship between ethnicity and teaching between sibling dyads; Hadza sibling dyads were more likely to exchange teaching than BaYaka sibling dyads when compared to non-kin ($\beta = -1.71$), and other kin (contrast = −1.84). However, there were no strong differences between Hadza and BaYaka sibling teaching when compared to parent-child dyads.

5.3. Sex

The main effects of teacher and learner sex were not strong predictors in the model. However, in support of prediction 5, we found that teaching was more likely to occur between same-sex than opposite-sex dyads ($\beta = 1.10$).

5.4. Random effects

In support of prediction 6, the variance and correlated random effects showed that dyadic reciprocity was high ($\sigma_{dd}^2 = 0.96$), and that 64% of the variation in the model could be explained by the effect of the relationship (*Ptl*). In addition, 15% of the variation in the model was explained by the effect of the teacher (*Pt*), 8% of the variation in the model was explained by the effect of the learner (*Pl*), and 13% of the variation was explained by the camp in which children inhabited (*Pc*).

6. Discussion

The present study aimed to investigate how age, sex, and kinship influenced the teaching of subsistence skills in BaYaka and Hadza forager 3- to 18-year-olds. Our findings suggest that Hadza and BaYaka children participated in teaching, either as a teacher or as a learner, between 6 and 8 times an hour. A majority of these teaching events occurred within child dyads. Alongside research among the Aka and Ngandu (Boyette & Hewlett, 2017a; Hewlett & Roulette, 2016), Baka (Gallois, Duda, Hewlett, & Reyes-garcía, 2015), Maya (Maynard, 2002; Zarger, 2002), and Fijians (Kline, 2016), our results highlight the central role Hadza and BaYaka children play as teachers, and not just acquirers, of cultural knowledge.

Children in both populations taught more with age, with overall teaching directed to children peaking in adulthood. Teaching likely develops with age because children's teaching abilities continue to increase, and because they have more knowledge to share with others (Strauss & Ziv, 2012). Though the development of children's teaching abilities have been documented in multiple societies in the industrialized west (see Strauss & Ziv, 2012 for review), our findings lend support to a growing body of evidence demonstrating that in non-western societies, this development occurs independently of intensive formal schooling (Boyette & Hewlett, 2017a; Maynard & Tovote, 2009). Interestingly, after approximately 30, the teaching of children actually decreased with age. Since, by 30, most adults have children who are old enough to teach their younger siblings, our findings may reflect children's participation in offsetting their cost of care. Children's participation in economic activities among the Maya likely increases mother's reproductive success (Lee & Kramer, 2002). By accelerating other children's subsistence knowledge acquisition through teaching, children may be increasing their inclusive fitness by promoting sibling self-sufficiency and shortening parental inter-birth interval. Children may also be improving their individual fitness by increasing their share of

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parental provisioning. Furthermore, children may liberate parents to teach more complex skills to adolescents and other adults, thus reducing the cost of cumulative cultural transmission.

Consistent with kin selection theory, teaching was more likely to occur between related dyads than unrelated dyads in both groups. However, when compared to non-kin and other-kin, sibling teaching was more common among the Hadza than among the BaYaka. We interpret these findings as indicating that teaching was more likely to occur within nuclear families among the Hadza compared to the BaYaka. We propose that these findings are related to camp structure. As noted earlier, BaYaka camps are typically more compact than Hadza camps (Hewlett et al., 2019) partially because of the constraints imposed by living in a forested environment rather than in the savannah. As a result, BaYaka children are invariably in closer proximity to all other camp members while in camp, while Hadza children can more easily assort with more closely related individuals, including siblings and parents. This may result in different teaching patterns, where other-kin and non-kin play a greater role in knowledge transmission for the BaYaka, whereas for the Hadza, the nuclear family may play a greater role in knowledge transmission. An alternative explanation may be simply that, because the Hadza have more siblings than the BaYaka, the former experienced more sibling teaching than the latter. However, Blurton Jones (2016) states that the total fertility rate for the Hadza is 5.3, while, for the BaYaka, total fertility rate is reported by Hewlett (1991) as 6.2, with similar infant mortality rates (~20% Blurton Jones, Hawkes, & O'Connell, 2002; Hewlett, 1991). Furthermore, as Table 1 shows, the BaYaka had proportionally more siblings in camp than the Hadza (5% vs. 3%), making it unlikely that number of siblings in camp explains the observed difference in Hadza and BaYaka sibling teaching. Thus, our results suggest that intra-site variation in settlement structure may influence the distribution of kin teaching. Future studies should further investigate this claim.

For the BaYaka only, younger children were more likely to be taught by other children while BaYaka adolescents were more likely to be taught by adults. This finding is consistent with the multistage model of knowledge acquisition, which suggests that children develop basic skills from other children before seeking skilled adults from whom they can update their knowledge, and who might also be more willing to teach individuals with the necessary baseline competence (Henrich & Henrich, 2010; Reyes-García et al., 2016). While our data support a multistage model of learning among the BaYaka, we found little difference in teacher's age for younger and older learners among the Hadza. While unexpected, this finding may be explained by examining foraging participation. Hadza children collect between 25 and 50% and sometimes even 100% of their daily caloric needs from an early age (Crittenden et al., 2013; Hawkes et al., 1995). Although children tend to target easier to access resources such as berries and baobab when they are younger, they are provided with opportunities to practice more complex resource acquisition throughout childhood; for example, boys as young as two are made small, functional bows and arrows, and girls are provided with small, appropriately sized digging sticks (Crittenden, 2016). Unlike among the BaYaka, children are fully expected to collect food with these tools. Thus, for the Hadza, teaching by adults may primarily occur through stimulus enhancement in early life, after which children are more likely to learn complex skills through participation in foraging with other children than through teaching by adults. Though a multistage learning model where children learn with other children when younger, and by adults when older may be more common, it may nonetheless depend on the foraging niche in which learning occurs. Future studies should thus take seriously the role of ecological context when investigating the distribution of learning processes across the lifespan.

Mathematical models investigating optimal learning strategies suggest that individual learning should occur only after children have acquired knowledge socially (Aoki, Wakano, & Lehmann, 2012; Borenstein, Feldman, & Aoki, 2008; Lehmann et al., 2013). Although previous studies of play (Bock & Johnson, 2004), observation (Greenfield, 2004), and teaching (Boyette & Hewlett, 2017a) found that social learning declined with age, presumably because older individuals have begun to refine learned behavior through individual practice, our final model found only a weak negative relationship between learner's age and teaching. However, we note that learner's age was a strong negative predictor in additional models which omitted this interaction (see supplementary materials). This suggests that what might first appear to be a decreasing likelihood for older individuals to be learners is actually better explained by (a) a decrease in teaching by older individuals, due to the declining latter portion of the quadratic 'teacher age' curve (Fig. 1), and (b) a tendency for teachers and learners to be of similar ages, as indicated by the positive teacher/learner age interactions. In other words, the decline in teaching by older individuals is sufficient to explain the decline in learning by older individuals as well.

As in other aspects of forager life (Allen-Arave et al., 2008; Crittenden & Zes, 2015; Peterson, 1993), we found evidence for high dyadic reciprocity, and a large effect of the dyad, in teaching. Researchers working with highly stratified cultures have found collaboration to enhance children's knowledge acquisition in experimental settings (Dean, Kendal, Schapiro, Thierry, & Laland, 2012; Dunn, 1983; Laland, 2004; Tomasello, 1999; Tomasello et al., 1993; Wood, Wood, Ainsworth, & Malley, 1995). When comparing collaborative problem solving across cultures, Nielsen, Mushin, Tomaselli, and Whiten (2016) found that Australian Indigenous children collaborated significantly more than Brisbane pre-schoolers (see also Rogoff, 1998). Since collaborative learning generates new knowledge forms (Tomasello, 1999; Tomasello et al., 1993), it may be especially adaptive to foragers relying on unpredictable resources. One limitation of our study is that we examined short-term reciprocity. A long term examination of teaching may show a different, and more unidirectional, pattern. Nonetheless, future studies should examine the advantages conferred by reciprocal knowledge sharing during daily interactions in childhood.

Finally, same-sex teaching was hypothesized to increase the likelihood that children would learn sex-specific skills (Henrich & Gil-White, 2001). Same-sex bias in learning has been noted among foragers the world over (Boyette & Hewlett, 2017a; Draper, 1975; Hewlett & Cavalli-Sforza, 1986; Lew-Levy, Lavi, Reckin, Cristóbal-Azkarate, & Ellis-Davies, 2018; MacDonald, 2007b). Here, we also found strong evidence for same-sex teaching among both the BaYaka and the Hadza.

7. Implications

Taken together, this paper sheds light on the evolutionary importance of, and cross-cultural variation in, child-to-child teaching. Most studies investigating the evolution of childhood have assumed that children require provisioning until at least adolescence (Kaplan et al., 2000), yet recent studies have challenged this claim, showing that children can be, and often are, producers (Bird & Bliege Bird, 2005; Crittenden et al., 2013; Tucker & Young, 2005), that children sometimes produce a surplus of calories which can be shared with the parental generation (Crittenden et al., 2013), and that children's production contributes to parental reproduction (Kramer, 2014; Lee & Kramer, 2002). Similarly, many studies on the evolution of cumulative culture assume that transmission only or primarily occurs from parents to offspring (e.g. Shennan & Steele, 1999), and that childhood is a sensitive period for knowledge acquisition (Kaplan et al., 2000). The results of the present paper problematize these claims because they demonstrate that children are active teachers from an early age. Child-to-child teaching may be especially adaptive because it has the potential to increase children's inclusive and individual fitness by offsetting their own, and their siblings' cost of care (Konner, 1976; Lee & Kramer, 2002). Furthermore, because children can facilitate each other's knowledge acquisition in the zone of proximal development, child-to-child teaching may contribute to more rapid, and potentially less costly, knowledge transfers for basic skills (Hewlett & Cavalli-Sforza, 1986).

Our analysis was limited by the fact that dyadic proximity data proved too difficult to collect while also keeping track of children's teaching and foraging activities. Dyadic proximity is important because individuals may choose to assort with the intent to share knowledge with each other. At least among the BaYaka, adults report inviting children to forage alongside them with the specific intent to teach subsistence skills (Lew-Levy et al., 2019). Similarly, BaYaka children sometimes preferred to forage in the absence of adults so that they could learn with their peers (Boyette & Lew-Levy, Under review). Alternatively, teaching may occur opportunistically while individuals are participating in other cooperative behaviors. For example, parents who forage with their children because they require assistants may also use a foraging trip as an opportunity to teach. Thus, future studies should examine whether teaching is independent from, or a by-product of, other social and cooperative relationships. Future studies should also examine whether cross-cultural differences in associative patterns translates to differences in teaching.

The present paper brings to light several areas for future research. Since fieldwork was only conducted during part of the year, we were unable to observe every foraging activity (e.g. *kombi* fishing for the BaYaka, weaver-bird collecting for the Hadza); future studies will examine how seasonal variation in child and adult foraging and diet influences how and from whom children learn (Crittenden & Schnorr, 2017; Gallois et al., 2015). In addition, as demonstrated in Table S3, we observed little teaching in especially complex domains, such as hunting and trapping. This may be because these skills are acquired later in life (Gurven, Kaplan, & Gutierrez, 2006; Ohtsuka, 1989; Walker et al., 2002). Since the age cut-off for the present study was approximately eighteen, more longitudinal studies on the distribution of knowledge acquisition across seasons, and in late adolescence and adulthood are needed. Studies comparing teaching to other social learning forms, such as observation and imitation, are also needed. Next, while the present paper considered teaching generally, future studies will examine whether different teaching types covary with the specific domain of subsistence being transmitted. Finally, the foragers with whom we worked had limited exposure to schooling. Future studies will examine how teaching patterns change with increased exposure to schools.

Ethics

Camp-wide, parental, and child verbal consent was obtained before data collection began. All consent procedures and research protocols were approved by the Cambridge Psychology Research Ethics Committee (PRE.2016.026). In country permission was received from the Tanzanian Commission for Science and Technology (COSTECH) and from Congo from the Centre de Recherche et D'Etudes en Sciences Sociales et Humaines (CRESSH).

Data accessibility

The datasets and code supporting this article are available from the corresponding author upon request.

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Author's contributions

All authors contributed to the study design. SLL collected the data with the help of IAM and AHB. SLL and SMK analyzed the data. SLL prepared the manuscript. All authors revised the manuscript, and approved the final version of the manuscript.

Declaration of Competing Interest

We have no competing interests.

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Appendix A. Supplementary materials

Supplementary materials for this article can be found online at https://doi.org/10.1016/j.evolhumbehav.2019.07.003.

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