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Impact of Family Networks on Uptake of Health Interventions: Evidence from a community-randomized control trial aimed at increasing HIV Testing in South Africa

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Complete List of Authors:	Makofane, Keletso ; Harvard University, Harvard FXB Center for Health and Human Rights Kim, Hae-Young; New York University Grossman School of Medicine, Population Health Tchetgen Tchetgen, Eric; Upenn Bassett, Mary; New York State Department of Health Berkman, Lisa; Harvard Center for Population and Development Studies Adeagbo, Oluwafemi; Africa Health Research Institute, Social Science & Ethics Unit McGrath, Nuala; University of Southampton Seeley, Janet; London School of Hygiene and Tropical Medicine Faculty of Public Health and Policy, Department of Global Health and Development; MRC/UVRI Uganda Research Unit On AIDS, Shahmanesh, Maryam; University College London, Institute for Global Health ; Africa Health Research Institute, Somkhele Yapa, H. Manisha; Africa Health Research Institute; University of New South Wales, The Kirby Institute Herbst, Kobus; Africa Health Research Institute Tanser, Frank; University of Lincoln Baernighausen, Till; Universitatsklinikum Heidelberg Institut fur Public Health
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Methods:
The 'Home-Based Intervention to Test and Start' (HITS) was a 2x2 factorial community-randomized controlled trial in Umkhanyakude, KwaZulu-Natal, South Africa, embedded in the Africa Health Research Institute's population-based demographic and HIV surveillance platform (ClinicalTrials.gov # NCT03757104).

The study investigated the impact of two interventions, a financial micro-incentive and a male-targeted HIV-specific decision support program. The surveillance area was divided into 45 community clusters. Of these, individuals aged ≥15 years in 16 randomly selected communities were offered a micro-incentive (R50 [$3] food voucher) for rapid HIV testing (intervention arm). Those living in the remaining 29 communities were offered testing only (control arm).

Using routinely collected data on parents, conjugal partners, and co-residents, a sociocentric family network was constructed among HITS-eligible individuals. Nodes in this network represent individuals and ties represent family relationships. We estimated the effect of offering the incentive to people with and without family members who also received the offer on uptake of HIV testing. We fitted a linear probability model with robust standard errors, accounting for clustering at the community level.
Results:

Overall, 15,675 people participated in the HITS trial. Among those with no family members who received the offer, the incentive's efficacy was a 6.5 percentage point increase (95% CI: 5.3 to 7.7). The efficacy was higher among those with at least one family member who received the offer (21.1 percentage point increase (95% CI: 19.9 to 22.3). The difference in efficacy was statistically significant (21.1 – 6.5 = 14.6%; 95% CI: 9.3 to 19.9).

Conclusions:
Micro-incentives appear to have synergistic effects when distributed within family networks. These effects support family network-based approaches for the design of health interventions.

Impact of Family Networks on Uptake of Health Interventions: Evidence from a community-randomized control trial aimed at increasing HIV Testing in South Africa

K. Makofane, PhD[1‡]
H.Y. Kim, PhD[2,3]
E. Tchetgen Tchetgen, PhD[4]
M.T. Bassett MD[1]
L. Berkman, PhD[1]
O. Adeagbo PhD[3]
N. McGrath ScD[3,5]
J. Seeley PhD[3,6]
M. Shahmanesh PhD[3,7]
H.M. Yapa, PhD[8]
K. Herbst, MBChB[3]
F. Tanser, PhD[3,9*]
T. Bärnighausen, ScD[3,10*]

Affiliations

1. Harvard University, 677 Huntington Avenue, Boston, MA 02115, United States
2. New York University Grossman School of Medicine, 227 East 30th Street, New York, NY, 10016, United States
3. Africa Health Research Institute, 719 Umbilo Road, Durban, 4001, South Africa
4. University of Pennsylvania, 255 South 38th Street, Philadelphia, PA 19104, United States
5. University of Southampton, Hartley Library B12, University Rd, Highfield, Southampton SO17 1BJ, United Kingdom
6. London School of Hygiene & Tropical Medicine, Keppel St, London WC1E 7HT, United Kingdom
7. University College London, Gower St, London WC1E 6BT, United Kingdom
8. University of New South Wales, Sydney NSW 2052, Australia
9. University of Lincoln, University of Lincoln, Brayford Pool, Lincoln, LN6 7TS, United Kingdom
10. University of Heidelberg, Grabengasse 1, 69117 Heidelberg, Germany

‡Corresponding Author (kmakofane@hsph.harvard.edu, +1 (617) 495-1000)

*F.Tanser and T. Bärnighausen are both senior authors

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ABSTRACT

Introduction:

While it is widely acknowledged that family relationships can influence health outcomes, their impact on uptake of individual health interventions is unclear. In this study, we quantified how the efficacy of a randomized health intervention is shaped by its pattern of distribution in the family network.

Methods:

The 'Home-Based Intervention to Test and Start' (HITS) was a 2x2 factorial community-randomized controlled trial in Umkhanyakude, KwaZulu-Natal, South Africa, embedded in the Africa Health Research Institute's population-based demographic and HIV surveillance platform (ClinicalTrials.gov # NCT03757104).

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Using routinely collected data on parents, conjugal partners, and co-residents, a sociocentric family network was constructed among HITS-eligible individuals. Nodes in this network represent individuals and ties represent family relationships. We estimated the effect of offering the incentive to people with and without family members who also received the offer on uptake of HIV testing. We fitted a linear probability model with robust standard errors, accounting for clustering at the community level.

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Conclusions:

Micro-incentives appear to have synergistic effects when distributed within family networks. These effects support family network-based approaches for the design of health interventions.

Introduction

Though family relationships crucially determine health and wellbeing, their role in shaping the uptake of individual health interventions is not well-understood. Using family network data from a large population-based cohort, we quantified the degree to which the efficacy of a randomized individual-level health intervention – a financial incentive for HIV Testing – is shaped by its pattern of distribution among family members.

Improving testing programs can increase access to anti-retroviral therapy (ART) which effectively eliminates HIV transmission at the individual level [1] and has substantially reduced population incidence [2–4]. Recognizing the uneven distribution of risk and access to services in so-called "generalized epidemics" [5], recent global public health guidance advocates multiple strategies for testing in these settings [6,7]. Interventions that leverage personal networks are among the most effective [6,7]. For instance, distributing HIV self-test kits to men through their sexual, romantic, and other social relationships has been shown to improve acceptability and uptake of testing [8–11]. Unrelated to networks but also effective are testing interventions that utilize financial incentives [12–14].

Through a post-hoc analysis of Home-Based Intervention to Test and Start (HITS) study data, we quantified how the effectiveness of a financial incentive for HIV testing changes depending on whether it is offered to an individual or offered to an individual along with family members. HITS, which was conducted in South Africa, investigated the effects on HIV testing and linkage to care of a ZAR 50 (USD 3) incentive and a male-targeted HIV-specific decision support program. We previously reported that among men, the uptake of HIV testing increased from 17.1% in standard of care to 27.5% in the financial incentives arm (Risk Ratio=1.55, 95% CI: 1.31 to 1.82) [12].

We build on this finding by testing the hypothesis that, for a given individual, the effectiveness of the financial incentive is augmented by offering incentives to family members prior to, or at the same time as, the individual. For many South Africans, resources are shared among extended family across different households [15]. It is possible, therefore, that over the course of the HITS trial, family members influenced each other's HIV testing behavior in order to maximize receipt of incentives.

Methods

Setting and Participants

HITS is a community-randomized controlled trial in the Hlabisa sub-district of the uMkhanyakude district – a rural region of northern KwaZulu-Natal with high HIV burden and unemployment [16–18]. It is nested in the Africa Health Research Institute's population-based demographic and HIV surveillance platform which follows 140,000 residents living in an area of 845 km^2 [16]. As part of annual routine HIV surveillance, trained field workers visit all households and record demographic information including parents, co-residents, and conjugal partners of each household member. During visits, all residents aged 15 years or older are offered home-based rapid HIV testing.

Individuals were eligible for HITS if they were 15 years or older at the time of surveillance visit, resided within the surveillance area, agreed to participate in annual HIV surveillance, and provided written informed consent for trial participation. Individuals were not eligible to participate in the trial if they refused to participate in HIV surveillance, reported being already on ART, or were mentally or physically unable to provide consent. The study is registered at the National Institute for Health's ClinicalTrials.gov (# NCT03757104). Further details are available in earlier publications [19].

Randomization and Masking

The HITS study investigated two interventions: a financial micro-incentive for HIV Testing and a male-targeted HIV-specific decision support program [12,19]. The surveillance area was divided into 45 community clusters which were randomized to study interventions using a 2x2 factorial design, permitting each intervention to be assessed separately. Interventions were delivered between February and November 2018. We consider the effect of the micro-incentive alone since the other study intervention was restricted to men whereas our analysis includes all HITS participants (see Figure 1).

The 45 communities were grouped into four strata based on baseline HIV incidence rates among women aged 15 — 30 years. The intervention arm consisted of four randomly selected communities from each of the four strata (16 communities total). The control arm consisted of the remainder of communities in each stratum (29 communities total). The study was an open label trial.

Consent and Intervention

Only residents who agreed to participate in annual AHRI HIV surveillance were eligible to participate in HITS. Residents were asked for their consent at the study visit. Those who consented to AHRI HIV surveillance were then asked for their consent to participate in the HITS study.

Those who were eligible for and consented to participate in HITS were enrolled. Those who resided in control communities were offered rapid HIV testing per the HIV surveillance protocol. Those in intervention communities were offered a micro-incentive conditional on undergoing home-based rapid HIV testing during the study visit. The micro-incentive was a food voucher valued at ZAR 50 (~USD 3), which was redeemable at a local supermarket [19].

Social Network

A sociocentric family network was constructed among HITS-eligible individuals using routinely collected surveillance data. Nodes in this network represent individuals. Three kinds of ties were added between the nodes: first-degree relatives (parents, children, and all conjugal partners of each participant), second degree relatives (the first-degree relatives of first-degree relatives), and co-resident relatives (individuals who ever resided in the same household as the participant and who were not tenants or domestic workers in that household). Below we refer to members of each person's personal family network (i.e. the egocentric network) simply as 'family members'.

Family members of residents are only recorded if they ever resided in the surveillance area. For most individuals, it was possible to identify at least one family member – only 2.7% (424/15,675) of HITS participants were not linked with any other residents. Because surveillance began in 2000, older residents were less likely to be observed at the same time as their parents. Among the records of individuals aged 15 - 25, 15.0% (2,321/15,458) were not linked to their mother's record and 48.3% (7,471/15,458) were not linked to their father's. Among those over 55 years of age, these proportions were 87.9% (4,795/5,458) and 97.3% (5,310/5,458) respectively. Missing linkages between participants and their parents indicate that their parents were not eligible for the study.

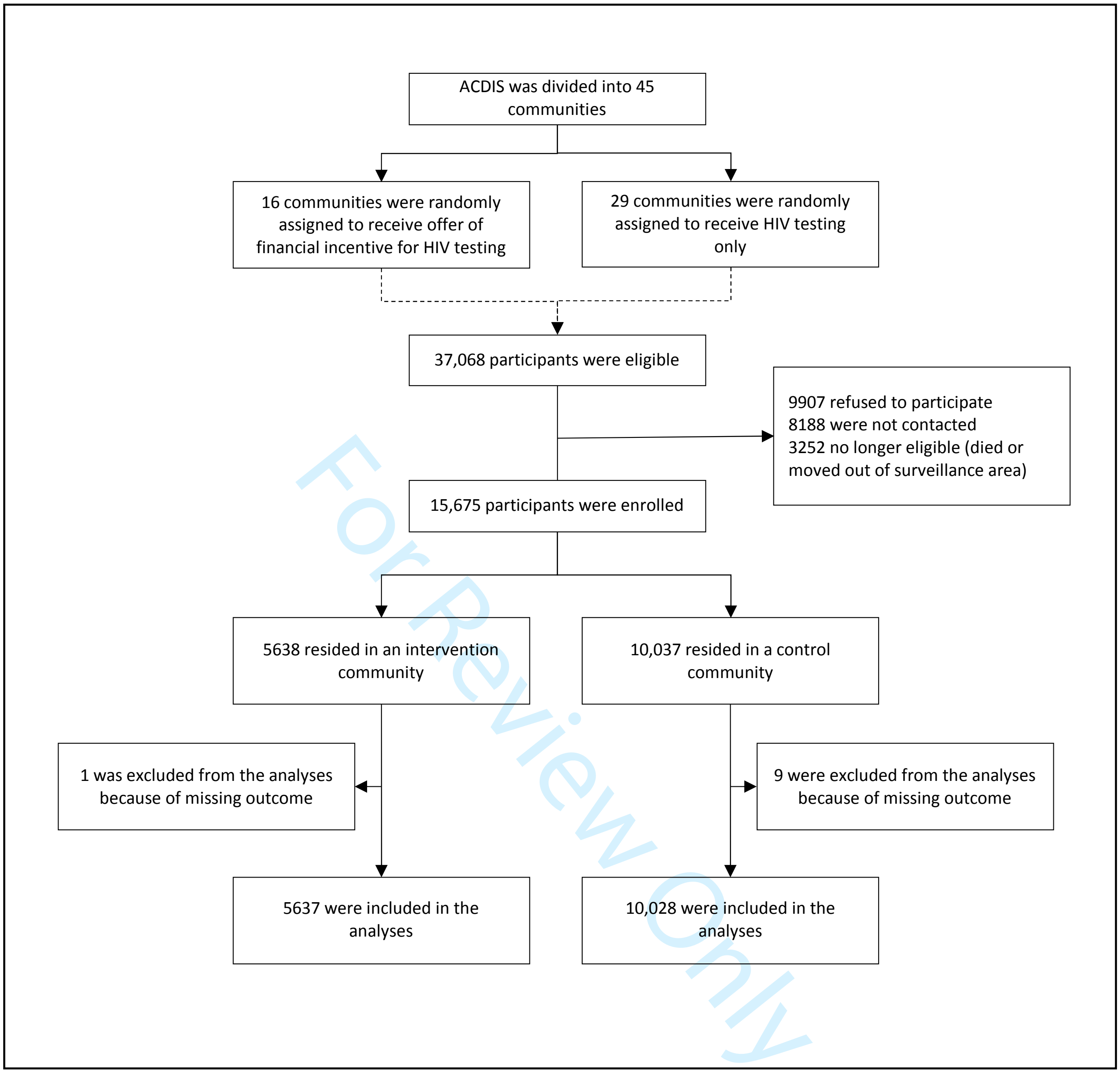

Figure 1: Flow diagram for HITS trial

Measures

The outcome of interest was individual uptake of rapid HIV testing at study visit. Exposures of interest were individual offer of financial incentive ('individual offer'), and family offer of incentive ('family offer'). For each participant, family offer was defined as the count of family members who were offered the financial incentive prior to or on the same day as the participant's own study visit. Network size was defined as the count of family members.

Analysis

We calculated sample characteristics, examined patterns of network connections between communities, and described the composition of network connections.

For the primary analysis we examined heterogeneity in the effect of the individual offer on HIV testing uptake across strata defined by dichotomized family offer ($\geq$ 1 vs. 0). We fitted a linear probability regression model with a two-way interaction encoding the extent to which the causal effect of individual offer is modified by dichotomized family offer. (See Measures sub-section for definition of 'family offer'). In a secondary analysis, we examined heterogeneity across strata defined by ordinal family offer. We fitted a linear probability model with two-way interaction terms encoding the extent to which the causal effect of individual offer is modified by family offer levels of zero, one, two, three, four, and five or more. We conducted a linear trend test. Finally, we conducted sensitivity analyses which we report in a supplementary note.

Models were fitted using robust standard errors, accounting for clustering at the community level. We did not formally adjust for multiple testing as we conducted only three hypothesis tests. Analysis was conducted by KM.

Missing Data

We conducted a complete case analysis as only 10/15,675 observations had missing outcome data. All other variables included in regression models were complete.

Power and Sample Size

The HITS sample size was calculated to detect a relative reduction of 25% or more in HIV incidence among females aged 15 to 30 with power exceeding 80% and $\alpha = 0.05$. Further details have been previously reported [19].

Ethics Statement

The Biomedical Research Ethics Committee of the University of KwaZulu-Natal approved study protocols for the AHRI's population-based HIV testing platform and HITS intervention (BE290/16 and BFC398/16) [12,19].

Role of the funding source

Study sponsors had no role in the design, data collection, analysis, interpretation, or write-up of this study, nor did they influence the decisions to submit the results for publication.

Conflicts of interest

The authors declare no conflicts of interest relating to this manuscript.

Results

Participants and Network

Of 37,068 residents who met inclusion criteria for the HITS study, 15,675 participated and 15,665 were included in the analysis (see Figure 1). 5638 participants lived in intervention communities (i.e. communities to whom an incentive was offered) and 10,037 in control communities. Further descriptive results have been previously reported [12].

It was common for participants to have family members in different households (60.4%, 9,468/15,675) and different communities (42.2%, 6,613/15,675) (see Table 1). However, compared to people living in control communities, people in intervention communities were more likely to have family members who live in an intervention community (85.1%, 4,799/5,638 vs. 9.4%, 945/10,037). This is because family member households are geographically clustered. Study arms were balanced on age, gender, HIV testing history, network size, and proportions of family members in different households and different communities.

Each community had family connections with almost every other community (see Figure 2). Overall, 77% (83,368/107,746) of connections were within communities (as opposed to across them). On average, communities in the control arm had 1947 (56,459/29) connections to individuals in other control communities whereas communities in the intervention arm had an average of 1682 (26,909/16) connections with individuals in other intervention communities. The proportion of connections that spanned intervention arms was 52% (11,178/ 21,507) for control communities and 80% (11,178/14,049) for intervention communities.

Two-thirds (64.7%, 3,647/5,637) of participants in the intervention arm agreed to take an HIV rapid test whereas half (50.7%, 5,087/10,028) of participants in the control arm agreed, leading to an overall risk difference of 13.6 (95% CI: 12.0 to 15.3). Of the 8734 participants who consented for an HIV test, HIV test results were recorded for 8700.

<u>Primary Analysis</u>

We found support for the hypothesis that the effect of the incentive on an individual's HIV testing uptake is augmented by offering incentives to their family members prior to, or at the same time as, them (See Figure 3). Among participants with at least one family member who was offered the incentive, the micro-incentive increased testing uptake by 21% (95% CI: 19.9 to 22.3). In contrast, among participants with no family members who were offered the incentive, the micro-incentive only increased testing uptake by 6.5% (95% CI: 5.3 to 7.7). The risk difference among the former group is 14.6% higher (95% CI: 9.3 to 19.9) that among the latter.

Secondary Analysis

The strength of the effect of the individual offer increased as more family members received a prior or contemporaneous offer of the incentive, further supporting the main hypothesis. Effect sizes increased from 6.5% (95% CI: 5.3-7.7) among participants with no family members who received the offer to 26.3% (95% CI: 23.5-29.0) among participants with three family members who received it. The effect size of the individual incentive appeared not to change substantially when four (RD: 25.5, 95% CI: 20.2-30.7) or five or more (RD: 24.8, 95% CI: 20.7-28.9) family members received the offer. A linear trend test showed that for each additional family member who was offered the incentive, the risk difference for the effect of the incentive on testing uptake increased by 4.8% (95% CI 2.4 to 7.2) on average.

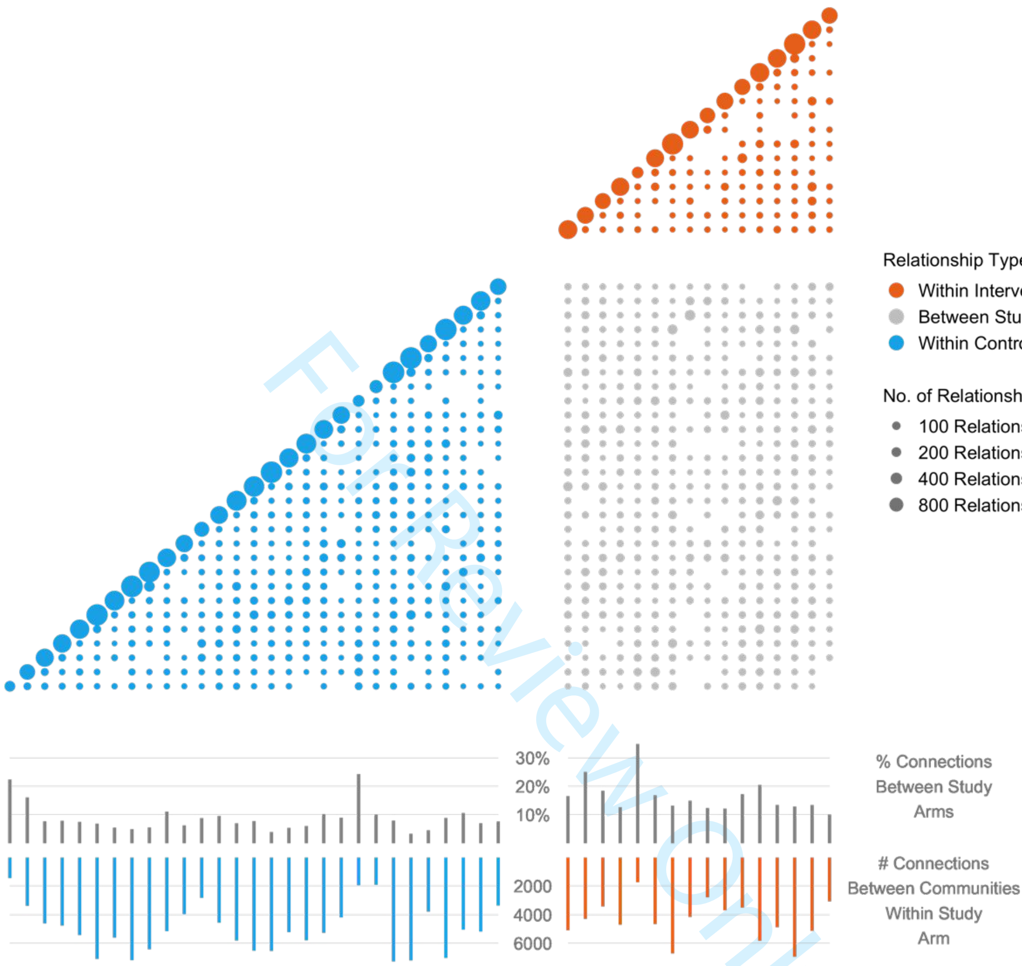

Figure 2: Family connections between communities in HITS study

The top part of the figure is a grid showing the number of family connections within each of the 45 randomization communities on the diagonal, and the number of family connections between each pair of communities below the diagonal. The size of the circles is proportional to the number of connections. Orange and blue bar graphs in the lower part of the diagram show the number connections across communities but within the intervention arm and control arm, respectively. The grey bar graph shows the proportion of connections across communities in different study arms. The diagram shows that each community was connected to almost every other community through family ties.

Subgroup	Control Clusters	Intervention Clusters	Efficacy (95% CI), P Value
	% (n/N)		
Dichotomized Family Treatment			
0	51 (4608/9029)	57·5 (775/1347)	6·5 (5·3 to 7·7), P<0·001
1+	45·6 (242/531)	66·6 (2695/4044)	21·1 (19·9 to 22·3), P<0·001
Ordinal Family Treatment			
0	51 (4608/9029)	57·5 (775/1347)	6·5 (5·3 to 7·7), P<0·001
1	46·5 (159/342)	64·2 (981/1528)	17·7 (16·3 to 19·1), P<0·001
2	45·4 (49/108)	69 (705/1021)	23·7 (21·7 to 25·7), P<0·001
3	42·5 (17/40)	68·8 (460/669)	26·3 (23·5 to 29), P<0·001
4	42·1 (8/19)	67·6 (225/333)	25·5 (20·2 to 30·7), P<0·001
5+	40·9 (9/22)	65·7 (324/493)	24·8 (20·7 to 28·9), P<0·001

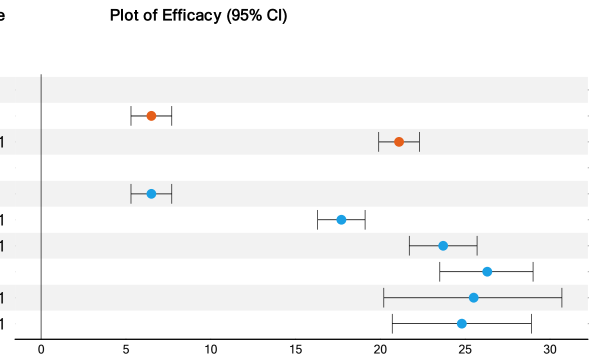

Figure 3: Effect Heterogeneity of HITS Intervention

The table shows results from the primary analysis (dichotomized family treatment) above and the secondary analysis (ordinal family treatment) below. Efficacy was calculated on the risk difference scale.

Discussion

The HITS study confirms that a modest community-wide financial incentive increases uptake of HIV testing. Our study establishes that an individual offered a financial incentive is more likely to take up testing when family members have received the same offer prior to or at the same time as them. The strength of the effect appears to increase with the count of family members in receipt of the offer.

This finding adds to a growing body of evidence from randomized control trials demonstrating that economic incentives increase the uptake of HIV testing [8,13,14,20–24] and improve clinical cascade outcomes more generally [25]. Past trials show consistent evidence that incentives improve treatment initiation [26,27], adherence to ART [22,28–32], and continuation in care [27,30]. They show mixed evidence that incentives improve linkage to care [26,27,33]. Despite their promise as a general-purpose HIV intervention, however, economic incentives have not been shown to lead to substantial reductions in incidence [34].

Though prior studies are often not explicit about the causal mechanism through which incentives are hypothesized to shape behavior, several explanations do appear in epidemiologic literature. Incentives can change the structural environment in which behavior unfolds (for instance, by alleviating poverty); they can affect the price of some behavior or good, or the income of the recipient in relation to that good or behavior; and they can intervene on the psychological processes that shape behavior [35,36]. In each case, studies commonly assume that the causal chain unfolds entirely *within* individuals and not across them.

There are some notable exceptions. Several trials have shown that incentivizing close social contacts – most commonly romantic [37,38] or sexual partners [39,40] or caregivers of children [21,41] – improves testing uptake. Furthermore, even in the absence of financial incentives, sexual and romantic partnerships have proven a useful conduit through which to deliver HIV testing services [9–11]. Our study extends these findings to demonstrate the impact of members of the family network in general, suggesting an opportunity to use a wider range of meaningful social relationships to reach individuals living with HIV with testing and other services.

Developing and applying theory that reflects the interdependence of individuals could enable the development of new interventions. For instance, family-based intervention strategies might be effective at reaching groups which otherwise have low access to health services, such as young people [17,42]. Because of high youth unemployment in South Africa [17,18], young people tend to depend on family members for material support [43]. They are likely to be connected with, and therefore reachable through, members of their family networks. To apply a behavioral economics analysis to this type of intervention, it would be useful to define the concepts of *utility* and *resources* at the group level, to understand decision-making as a collective (rather than individual) process, and to understand the impact of cognitive biases on this collective process.

We make a novel contribution to the fields of study design and applied causal inference. Our results show empirical evidence for the violation of the assumption of "partial interference" in the context of a large-scale cluster-randomized trial [44]. The assumption holds that while individuals within clusters might influence each other's outcomes, individuals across distinct clusters do not. It underpins the interpretation of the difference in average outcomes (comparing intervention and control arms) as an overall treatment effect [44]. When there are substantial connections across clusters, failing to account for them might lead to biased or uninterpretable effect estimates.

It is likely that there are important social relationships that are relevant to HIV testing that were not captured in population surveillance data. This is a limitation of our study. Further research should develop methods to account for missing network data and design new approaches to measuring sociocentric networks. A further limitation is that we used the assumption of partial interference to calculate standard errors, though we show this assumption to be violated. This was motivated by the fact that network connections are much denser within clusters than they are across them; we do not expect this analytic decision to lead to anti-conservative estimates of uncertainty. Finally, we did not adjust for multiple testing, though we note that using the

Bonferroni correction (i.e. using a nominal Type I error rate of 0.05/3 = 0.017) would not have altered the main conclusions of this study.

A major strength of our findings is that they are not susceptible to homophily bias – bias that arises because of the tendency for people with similar unmeasured characteristics to form relationships based on those characteristics [45]. This is because the study intervention was randomly assigned after the formation of family relationships. A further strength is the applicability of our approach in different settings: it is feasible to conduct a family network analysis using data from any study embedded in the health and demographic surveillance systems of South Africa. Finally, sensitivity analyses show the estimates presented in the main analysis to be conservative.

Understanding humans in the context of their relationships can lead to improvements in population health. There is an urgent need to cultivate robust social network data for epidemiologic analysis – whether by collecting them, constructing them from already collected study data as we did here, or connecting passively collected information, such as social media data, with large public health datasets.

Conclusions

By combining family network data with data from a field experiment, we showed that network-based financial incentive programs for a behavioral health intervention might be more efficient than individual-based programs. Future HIV testing studies should assess interventions targeted at networks. More generally, public health studies should leverage data on participants' social networks to generate new insights about population health and to spur on the development of new intervention approaches.

Data Sharing Statement

Study data, including deidentified participant data and data dictionaries, are available for download from the AHRI Data Repository subject to the submission and approval of a study proposal.

Author Contributions

KM conducted analysis and drafted manuscript. ETT, MTB, LB edited manuscript. KM developed analytic plan with ETT, HYK, and TB. FT and TB accessed and verified all underlying data. All authors discussed and reviewed manuscript.

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Table 1: Baseline Characteristics

	Control Arm (N=10037)	Incentive Arm (N=5638)	Overall (N=15675)
Age			
15-25	3920 (39.1%)	2292 (40.7%)	6212 (39.6%)
26-35	1690 (16.8%)	922 (16.4%)	2612 (16.7%)
36-45	1194 (11.9%)	679 (12.0%)	1873 (11.9%)
46-55	1247 (12.4%)	695 (12.3%)	1942 (12.4%)
>55	1986 (19.8%)	1050 (18.6%)	3036 (19.4%)
Gender			
Female	6974 (69.5%)	3829 (67.9%)	10803 (68.9%)
Male	3063 (30.5%)	1809 (32.1%)	4872 (31.1%)
Ever Tested HIV+			
Yes	1796 (17.9%)	1029 (18.3%)	2825 (18.0%)
No	6344 (63.2%)	3716 (65.9%)	10060 (64.2%)
Refused	113 (1.1%)	61 (1.1%)	174 (1.1%)
Missing	1784 (17.8%)	832 (14.8%)	2616 (16.7%)
Family Network Size			
0	290 (2.9%)	134 (2.4%)	424 (2.7%)
1-5	5365 (53.5%)	3029 (53.7%)	8394 (53.6%)
6-10	3064 (30.5%)	1723 (30.6%)	4787 (30.5%)
11-15	961 (9.6%)	539 (9.6%)	1500 (9.6%)
16+	357 (3.6%)	213 (3.8%)	570 (3.6%)
Percentage of Family Members in Different Household			
0%	3990 (39.8%)	2217 (39.3%)	6207 (39.6%)
0-20%	820 (8.2%)	438 (7.8%)	1258 (8.0%)
20-40%	1484 (14.8%)	909 (16.1%)	2393 (15.3%)
40-60%	1390 (13.8%)	792 (14.0%)	2182 (13.9%)
60-80%	1343 (13.4%)	727 (12.9%)	2070 (13.2%)
80-100%	571 (5.7%)	313 (5.6%)	884 (5.6%)
100%	439 (4.4%)	242 (4.3%)	681 (4.3%)

	Control Arm (N=10037)	Incentive Arm (N=5638)	Overall (N=15675)
Percentage of Family Members in Different Community			
0%	5831 (58.1%)	3231 (57.3%)	9062 (57.8%)
0-20%	1237 (12.3%)	655 (11.6%)	1892 (12.1%)
20-40%	1269 (12.6%)	759 (13.5%)	2028 (12.9%)
40-60%	803 (8.0%)	486 (8.6%)	1289 (8.2%)
60-80%	537 (5.4%)	320 (5.7%)	857 (5.5%)
80-100%	189 (1.9%)	88 (1.6%)	277 (1.8%)
100%	171 (1.7%)	99 (1.8%)	270 (1.7%)
Network Treatment (# Family Members in Incentive Arm and who have Prior Study Visit)			
0	9092 (90.6%)	839 (14.9%)	9931 (63.4%)
1	551 (5.5%)	1205 (21.4%)	1756 (11.2%)
2	175 (1.7%)	1088 (19.3%)	1263 (8.1%)
3	77 (0.8%)	810 (14.4%)	887 (5.7%)
4	50 (0.5%)	570 (10.1%)	620 (4.0%)
5+	92 (0.9%)	1126 (20.0%)	1218 (7.8%)

Supplementary Note on Sensitivity Analyses

Impact of Family Networks on Uptake of Health Interventions: Evidence from a community-randomized control trial aimed at increasing HIV Testing in South Africa

K. Makofane, PhD
H.Y. Kim, PhD

Despite being a cluster-randomized controlled trial, the HITS study could have been vulnerable to selection bias for study participation, potentially due to factors beyond the control of the investigators. This could have implications for bias in the study results (i.e. the extent to which the statistical estimator we used systematically deviates from the 'true' underlying causal parameter under investigation), and for generalizability (i.e. the extent to which the 'true' underlying causal parameter among study participants accurately reflects the underlying causal parameter among the population from which survey participants were sampled).

Using sensitivity analysis, we examine the likelihood and extent to which the causal estimate reported in our study is unbiased and generalizable.

Survey Enrollment

To enroll in the HITS study, participants had to go through a three-layer consent process. First, residents were asked if they consent for the study visit. Among those who consented, individuals were asked if they consent to the annual HIV surveillance conducted by AHRI. Finally, among those who consented to the HIV surveillance, participants were asked if they consented for the HITS study.

Because the intervention status of clusters was not concealed from potential participants, there is possibility that their decision to participate in the study may have been influenced by their exposure status. We examine the potential impact of this on the causal estimand under study.

Bias

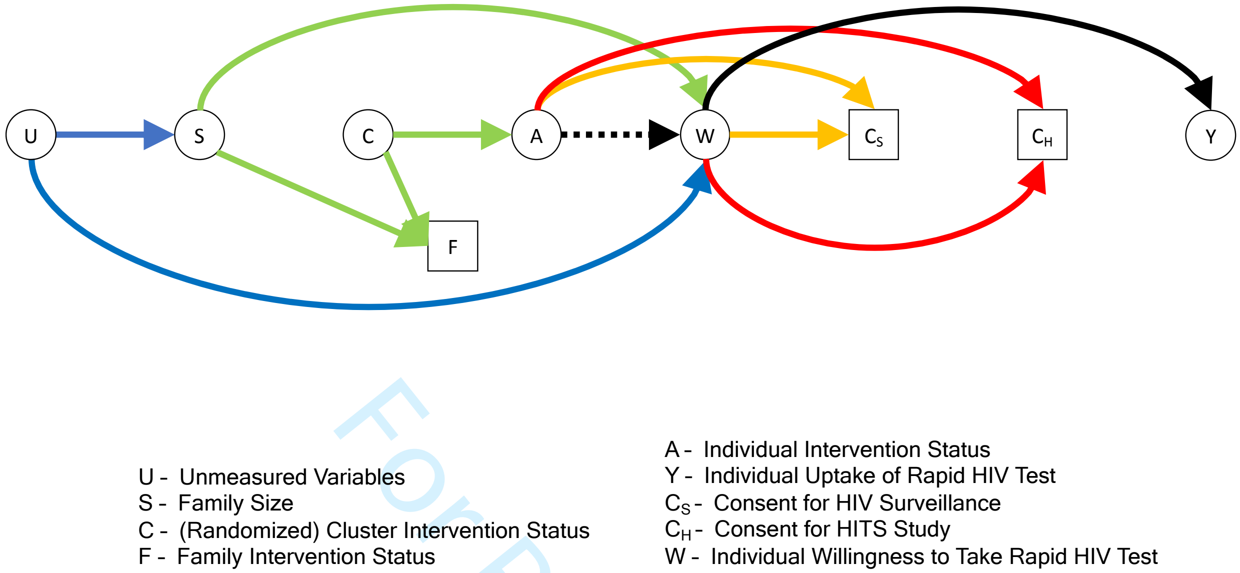

Figure S1: Directed Acyclic Graph for HITS Study Selection

Causal Assumptions

Figure S1 shows a representation of the causal theory underpinning our analysis. Solid arrows represent causal pathways we assume exist, and the dotted arrow shows the causal pathway under investigation. Circles represents variables, and squares represent variables on which the analysis is conditioned.

Individual willingness to take a rapid HIV test (W) is assumed to be caused by Family Intervention Status (F – a variable measuring whether the participant's family members received the offer the incentive), family size (S), and other unmeasured variables (U).

Individual offer of the financial incentive (A) is assumed to be caused exclusively by the intervention status of the community (C). Family intervention status (F) is caused by C as well as S.

We hypothesize that the individual receipt of the offer of an incentive (A), causes willingness to take a rapid HIV test (W). We assume that the effect of all prior variables on Y is mediated exclusively by W.

Finally, we assume that consent for HIV surveillance (C_s) is caused by W, among other variables. Consent for the HITS study (C_H) is also caused by W, among other variables. The analysis is conditioned on C_s and C_H since we only observe participants who consented to both HIV surveillance, and HITS. Since we examine the $A \rightarrow Y$ relationship within levels of F, the analysis is conditioned on F as well.

Implications for Bias

Under the assumptions that

a) people who desire to take an HIV test are more likely to consent to the HIV surveillance and to the HITS study and,
b) people who know that they are in the intervention arm are more likely to participate in the study

we would find that the effect of one's own intervention status on one's likelihood to test is biased in the negative direction. This would be a result of collider stratification bias as defined through the rules of D-Separation (Hernán and Robins 2018).

i.e. According to the Directed Acyclic Graph (DAG) shown in Figure S1, there are two backdoor paths connecting one's individual intervention status (A) with the study outcome which is uptake of rapid HIV testing (Y): $A \rightarrow \boxed{C_H} \leftarrow W \rightarrow Y$ and $A \rightarrow \boxed{C_S} \leftarrow W \rightarrow Y$. These backdoor paths would tend to bias the measured relationship between A and Y in the negative direction.

However, since we examine the relationship between individual exposure status (A) and the outcome (Y) within strata defined by family intervention status (F), we open the backdoor paths $A \leftarrow C \rightarrow \boxed{F} \leftarrow S \leftarrow U \rightarrow W \rightarrow Y$ and $A \leftarrow C \rightarrow \boxed{F} \leftarrow S \rightarrow W \rightarrow Y$. To close these backdoor paths, it is sufficient to condition on family size (S). Therefore, after adjusting for family size, the only backdoor paths connecting exposure and outcome bias the effect estimates within strata defined by F. These paths will tend to bias the relationship between A and Y in the negative direction.

We note that the causal estimand of interest is not the stratum-specific effects of A on Y, it is the difference between the effect sizes. Bias in the causal estimand of interest would occur if the effect estimate in one stratum was biased to a different extent than the effect estimate in the other stratum.

Defining δ as the causal estimand of interest, δ_- as the effect of the individual incentive on HIV Testing uptake among those whose family members were not offered the incentive, and δ_+ as the effect among those whose family members were offered the incentive, we have:

$$\delta \equiv \delta_+ - \delta_-$$

Further defining $\hat{\delta}$, $\hat{\delta}_+$, and $\hat{\delta}_-$ as the statistical estimators for parameters δ, δ_+, and δ_-, respectively:

$$\begin{aligned} Bias[\hat{\delta}] &= \delta - E[\hat{\delta}] \\ &= \delta_+ - \delta_- - E[\hat{\delta}_+ - \hat{\delta}_-] \\ &= Bias[\hat{\delta}_+] - Bias[\hat{\delta}_-] \end{aligned}$$

Say we estimated $\hat{\delta}$ as having a positive point estimate with confidence interval $[ci_{lb} - ci_{ub}]$ where $ci_{lb}, ci_{ub} > 0$, and we believed that this estimate is possibly biased by collider-stratification. Following VanderWheele et al. (2017), we would say the bias explains away the causal estimate if removing the bias caused the confidence interval to shift so that it includes 0. i.e. The causal estimate is explained away by bias if:

$$ci_{lb} - Bias[\hat{\delta}] \leq 0$$
$$Bias[\hat{\delta}_+] - Bias[\hat{\delta}_-] \geq ci_{lb}$$

Table S1, below, shows the stratum specific effect sizes, and the difference in effect sizes both in the original analysis (upper half of the table) and an analysis which is conditioned on family size (lower half of the table). Referring to the conditional analysis, $\hat{\delta}$ is estimated as 17.5 with a 95% confidence interval of (7.3 to 27.7). For the main conclusion of the study to be explained away by the bias induced by the open backdoor paths described above, the bias of the effect size among those with no family members who were offered the incentive would have to be larger (in absolute terms on the linear scale) by 7.3 percentage points (the lower bound of the confidence interval) than the bias among those with family members who received the offer.

Table S1: Stratum-specific causal estimates for a financial incentive for HIV Testing

	Family Not Offered Incentive	**Family Offered Incentive**	**Difference in Effect Sizes**	**p**
Unadjusted				
Individual Not Offered Incentive	51.0 (1.3)	45.6 (2.3)		
Individual Offered Incentive	57.5 (2.0)	66.6 (1.2)		
Effect of Individual Incentive	6.5 (1.5 to 11.5)	21.1 (15.7 to 26.5)	14.6 (8.1 to 21.0)	0.000
p	0.012	0.000		
Adjusting for Family Size				
Individual Not Offered Incentive	51.1 (1.2)	46.1 (3.3)		
Individual Offered Incentive	53.8 (3.5)	66.2 (1.2)		
Effect of Individual Incentive	2.6 (-5.7 to 10.9)	20.1 (13.2 to 27.0)	17.5 (7.3 to 27.7)	0.001
p	0.536	0.000		

Generalizability

Table S2: Participation in HIV Surveillance by Age and Gender

	Refused HIV Surveillance (N=9907)	Participated in HIV Surveillance (N=15675)	Overall (N=25582)	P-value
Gender				
Female	5133 (51.8%)	10803 (68.9%)	15936 (62.3%)	<0.001
Male	4774 (48.2%)	4872 (31.1%)	9646 (37.7%)	
Age				
Mean (SD)	34.2 (18.1)	35.3 (19.6)	34.9 (19.0)	<0.001
Median [Min, Max]	30.3 [8.78, 95.5]	30.7 [10.1, 99.7]	30.5 [8.78, 99.7]	
Missing	2 (0.0%)	2 (0.0%)	4 (0.0%)	

As shown is Table S2, women were more likely than men to consent to HIV surveillance, and older people were more likely than younger people to consent. To the extent that age or sex modify the relationship between the study exposure and outcome, these differences in study participation might indicate that study results are not generalizable to the underlying population.

To bring the study sample closer to the underlying population, we conducted the analyses whose results are shown in Table S1 again, this time, using inverse probability of selection weights. The weights were constructed using a logistic regression model with study participation as outcome, gender as a categorical variable, and age as a degree-2 polynomial. The results, shown in Table S3 below. The difference in effect sizes between strata decreases by 0.1 percentage points, and the lower bound decreases by 0.2 percentage points.

Table S3: Stratum-specific causal estimates for a financial incentive for HIV Testing (with inverse probability of selection weighting)

	Family Not Offered Incentive	Family Offered Incentive	Difference in Effect Sizes	p
Unadjusted				
Individual Not Offered Incentive	51.4 (1.4)	45.7 (2.5)		
Individual Offered Incentive	58.0 (1.9)	66.7 (1.2)		
Effect of Individual Incentive	6.6 (1.9 to 11.4)	21.0 (15.8 to 26.2)	14.4 (8.0 to 20.9)	0.000
p	0.006	0.000		
Adjusting for Family Size				
Individual Not Offered Incentive	51.5 (1.2)	46.4 (3.3)		
Individual Offered Incentive	54.4 (3.3)	66.3 (1.3)		
Effect of Individual Incentive	2.9 (-4.7 to 10.4)	19.9 (13.4 to 26.3)	17.0 (7.1 to 26.9)	0.001
	0.454	0.000		

Conclusions

Conditioning on family size yields a larger causal estimate than the one presented as the main study result. The result is, therefore, conservative. Furthermore, using inverse probability of selection weights to adjust for potential selection bias does not materially change the causal estimate.

It is possible that the main estimate is biased by collider-stratification bias in each stratum defined by family intervention status. For this to explain away the main study finding, it would have to be the case that the difference in the magnitude of the bias in each stratum is at least 7.3 percentage points. We therefore conclude that the main study findings are robust to this type of bias.

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Impact of Family Networks on Uptake of Health Interventions: Evidence from a community-randomized control trial aimed at increasing HIV Testing in South Africa

K. Makofane, PhD[1‡]
H.Y. Kim, ~~DrPH[2]~~PhD[2,3]
E. Tchetgen Tchetgen, PhD[4]
M.T. Bassett MD[1]
L. Berkman, PhD[1]
O. Adeagbo PhD[3]
N. McGrath ScD[3,5]
J. Seeley PhD[3,6]
M. Shahmanesh PhD[3,7]
H.M. Yapa, PhD[8]
K. Herbst, MBChB[3]
F. Tanser, PhD[3,9*]
T. Bärnighausen, ScD[3,10*]

Affiliations

1. Harvard University, 677 Huntington Avenue, Boston, MA 02115, United States
2. New York University~~, 50 West 4th~~ Grossman School of Medicine, 227 East 30th Street, New York, NY, ~~10012~~10016, United States
3. Africa Health Research Institute, 719 Umbilo Road, Durban, 4001, South Africa
4. University of Pennsylvania, 255 South 38th Street, Philadelphia, PA 19104, United States
5. University of Southampton, Hartley Library B12, University Rd, Highfield, Southampton SO17 1BJ, United Kingdom
6. London School of Hygiene & Tropical Medicine, Keppel St, London WC1E 7HT, United Kingdom
7. University College London, Gower St, London WC1E 6BT, United Kingdom
8. University of New South Wales, Sydney NSW 2052, Australia
9. University of Lincoln, University of Lincoln, Brayford Pool, Lincoln, LN6 7TS, United Kingdom
10. University of Heidelberg, Grabengasse 1, 69117 Heidelberg, Germany

‡Corresponding Author (kmakofane@hsph.harvard.edu, +1 (617) 495-1000)

*F.Tanser and T. Bärnighausen are both senior authors

Keywords: HIV Epidemiology, Testing, Social Networks, Randomized Controlled Trial (RCT), AHRI, Social Epidemiology

ABSTRACT

Introduction:

~~Though~~While it is widely acknowledged that family relationships ~~are known to shape~~can influence health outcomes, their impact on uptake of individual health interventions is ~~not well-understood. We~~unclear. In this study, we quantified~~, for the first time,~~ how the efficacy of a randomized health intervention is shaped by its pattern of distribution in the family network.

Methods:

The 'Home-Based Intervention to Test and Start' (HITS) ~~is~~was a 2x2 factorial community-randomized controlled trial ~~of 45 communities~~ in Umkhanyakude, KwaZulu-Natal, South Africa, embedded in the Africa Health Research Institute's population-based demographic and HIV surveillance platform (ClinicalTrials.gov # NCT03757104~~), among which~~).

The study investigated the impact of two interventions, a ~~sociocentric family network was constructed. Individuals~~financial micro-incentive and a male-targeted HIV-specific decision support program. The surveillance area was divided into 45 community clusters. Of these, individuals aged ≥15 years in 16 randomly selected communities were offered a micro-incentive (R50 [$3] food voucher) for rapid HIV testing (intervention arm). Those living in the remaining 29 communities were offered testing only (control arm).

~~In a post-hoc analysis, we~~Using routinely collected data on parents, conjugal partners, and co-residents, a sociocentric family network was constructed among HITS-eligible individuals. Nodes in this network represent individuals and ties represent family relationships. We estimated the effect of offering the incentive to people with and without family members who also received the offer~~.~~ on uptake of HIV testing. We fitted a linear probability model with robust standard errors, accounting for clustering at the community level.

Results:

Overall, 15,675 people participated in the HITS trial. Among those with no family members who received the offer, the incentive's efficacy was a 6.5% percentage point increase (95% CI: 5.3 to 7.7, P<0.001) on the risk difference scale.). The efficacy was 14.6% higher (95% CI: 9.3 to 19.9, P<0.001) among those with at least one family member who received the offer; efficacy in this group was (21.1% percentage point increase (95% CI: 19.9 to 22.3, P<0.001). The difference in efficacy was statistically significant (21.1 – 6.5 = 14.6%; 95% CI: 9.3 to 19.9).

ConclusionConclusions:

Micro-incentives appear to have synergistic effects when distributed within family networks. These effects support family network-based approaches for the design of health interventions.

Introduction

Though family relationships crucially determine health and wellbeing, their role in shaping the uptake of individual health interventions is not well-understood. Using family network data from a large population-based cohort, we quantified~~, for the first time,~~ the degree to which the efficacy of a randomized individual-level health intervention – a financial incentive for HIV Testing – is shaped by its pattern of distribution among family members.

Improving testing programs can increase access to anti-~~Retroviral~~retroviral therapy (ART) which effectively eliminates HIV transmission at the individual level [1] and has substantially reduced population incidence [2–4]. Recognizing the uneven distribution of risk and access to services in so-called "generalized epidemics" [5], recent global public health guidance advocates multiple strategies for testing in these settings [6,7]. Interventions that leverage personal networks are among the most effective [6,7]. For instance, distributing HIV self-test kits to men through their sexual, romantic, and other social relationships has been shown to improve acceptability and uptake of testing [8–11]. Unrelated to networks but also effective are testing interventions that utilize financial incentives [12–14].

Through a post-hoc analysis of Home-Based Intervention to Test and Start (HITS) study data, we quantified how the effectiveness of a financial incentive for HIV testing changes depending on whether it is offered to an individual or offered to an individual along with family members. HITS, which was conducted in South Africa, investigated the effects on HIV testing and linkage to care of a ZAR 50 (USD 3) incentive and a male-targeted HIV-specific decision support program. We previously reported that among men, the ~~incentive increased~~ uptake of HIV testing ~~by 55%~~increased from 17.1% in standard of care to 27.5% in the financial incentives arm (Risk Ratio=1.55, 95% CI: 1.31 to 1.82~~, P<0.001) compared to standard of care~~) [12].

We build on this finding by testing the hypothesis that, for a given individual, the effectiveness of the financial incentive is augmented by offering incentives to family members prior to, or at the same time as, the individual. For many South Africans, resources are shared among extended family across different households [15]. It is possible, therefore, that over the course of the HITS trial, family members influenced each other's HIV testing behavior in order to maximize receipt of incentives.

Methods

Setting and Participants

HITS is a community-randomized controlled trial in the Hlabisa sub-district of the uMkhanyakude district – a rural region of northern KwaZulu-Natal with high HIV burden and unemployment [16–18]. It is nested in the Africa Health Research Institute's population-based demographic and HIV surveillance platform which follows 140,000 residents living in an area of 845 km^2 [16]. ~~Annually~~As part of annual routine HIV surveillance, trained field workers visit all households and record demographic information including parents, co-residents, and conjugal partners of each household member. During visits, all residents aged 15 years or older are offered home-based rapid HIV testing.

Individuals were eligible for HITS if they were 15 years or older at the time of surveillance visit, resided within the surveillance area, agreed to participate in annual HIV surveillance, and provided written informed consent for trial participation. Individuals were not eligible to participate in the trial if they refused to participate in HIV surveillance, reported being already on ART, or were mentally or physically unable to provide consent. The study is registered at the National Institute for Health's ClinicalTrials.gov (# NCT03757104). Further details are available in earlier publications [~~12~~19].

Randomization and Masking

The HITS study investigated two interventions: a financial micro-incentive for HIV Testing and a male-targeted HIV-specific decision support program [12,19]. The surveillance area was divided into 45 community clusters which were randomized to study interventions using a 2x2 factorial design, permitting each intervention to be assessed separately. Interventions were delivered between February and November 2018. We consider the effect of the micro-incentive alone since the other study intervention was restricted to men whereas our analysis includes all HITS participants (see Figure 1).

The 45 communities were grouped into four strata based on baseline HIV incidence rates among women aged 15 — 30 years. The intervention arm consisted of four randomly selected communities from each of the four strata (16 communities total). The control arm consisted of the remainder of communities in each stratum (29 communities total). The study was an open label trial.

Consent and Intervention

~~HITS~~ Only residents who agreed to participate in annual AHRI HIV surveillance were eligible ~~individuals~~to participate in HITS. Residents were asked for their consent at the study visit. Those who consented to AHRI HIV surveillance were then asked for their consent to participate in the HITS study.

Those who were eligible for and consented to participate in HITS were enrolled. Those who resided in control communities were offered rapid HIV testing per the HIV surveillance protocol. Those ~~living~~ in intervention communities were offered a micro-incentive ~~for~~conditional on undergoing home-based rapid HIV testing~~, consisting of~~ during the study visit. The micro-incentive was a food voucher valued at ZAR 50 (~USD 3~~).~~), which was redeemable at a local supermarket [19].

Social Network

A sociocentric family network was constructed among HITS-eligible individuals using routinely collected surveillance data. Nodes in this network represent individuals. Three kinds of ties were added between the nodes: first-degree relatives (parents, children, and all conjugal partners of each participant), second degree relatives (the first-degree relatives of first-degree relatives), and co-resident relatives (individuals who ever resided in the same household as the participant and who were not tenants or domestic workers in that household). Below we refer to members of each person's personal family network (i.e. the egocentric network) simply as 'family members'.

Family members of residents are only recorded if they ever resided in the surveillance area. For most individuals, it was possible to identify at least one family member – only 2.7% (424/15,675) of HITS participants were not linked with any other residents. Because surveillance began in 2000, older residents were less likely to be observed at the same time as their parents. Among the records of individuals aged 15 - 25, 15.0% (2,321/15,458) were missing information onnot linked to their mothermother's record and 48.3% (7,471/15,458) were missing information onnot linked to their fatherfather's. Among those over 55 years of age, these proportions were 87.9% (4,795/5,458) and 97.3% (5,310/5,458) respectively. Missing linkages between participants and their parents indicate that their parents were not eligible for the study.

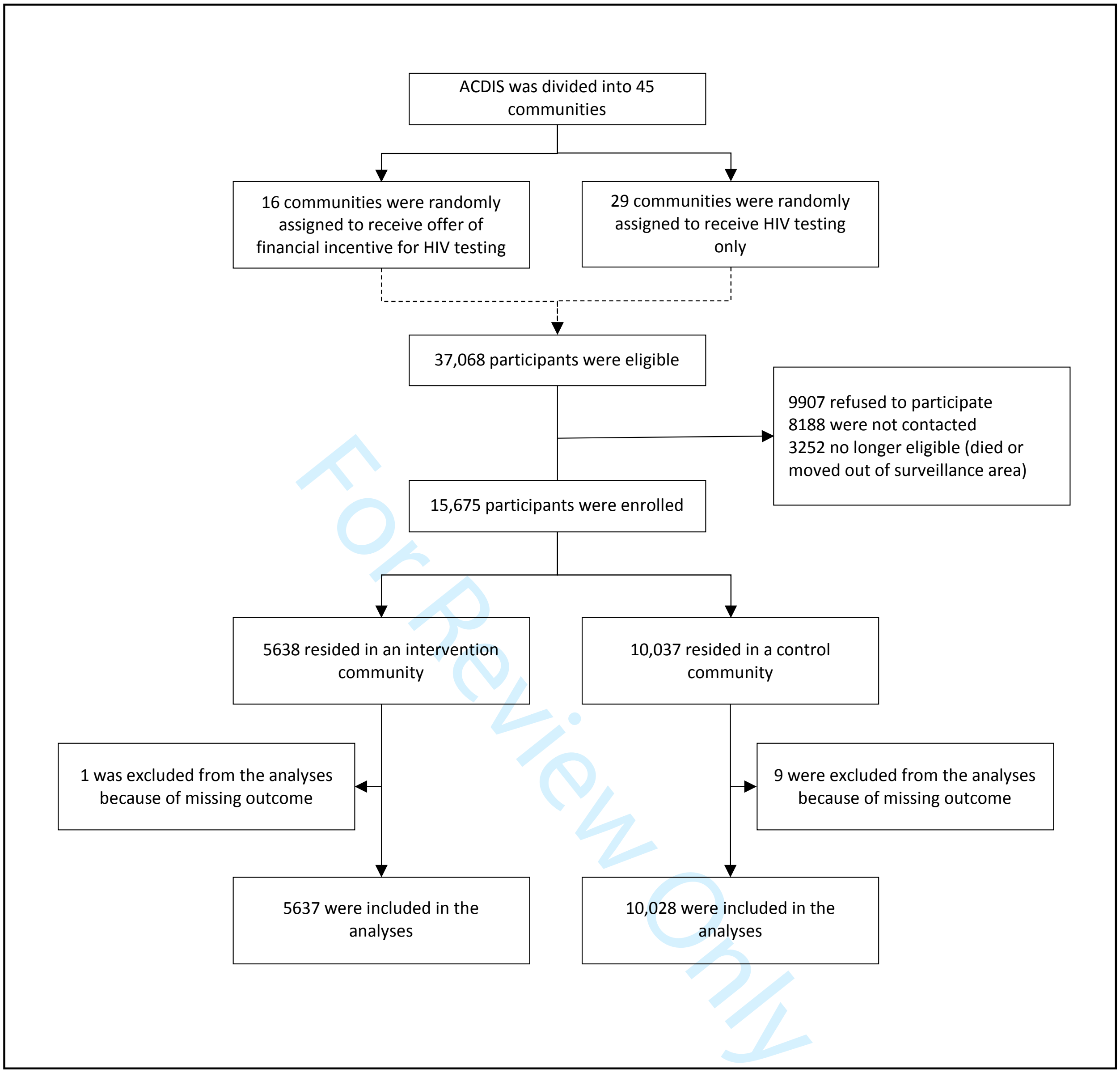

Figure 1: Flow diagram for HITS trial

Measures

The outcome of interest was individual uptake of rapid HIV testing at study visit, measured as consent for the test.. Exposures of interest were individual offer of financial incentive ('individual offer'), and family offer of incentive ('family offer'). For each participant, family offer was defined as the count of family members who were offered the financial incentive prior to or on the same day as the participant's own study visit. Network size was defined as the count of family members.

Analysis

We calculated sample characteristics, examined patterns of network connections between communities, and described the composition of network connections.

For the primary analysis we examined heterogeneity in the effect of the individual offer on HIV testing uptake across strata defined by dichotomized family offer (≥ 1 vs. 0). We fitted a linear probability regression model with a two-way multiplicative interaction encoding the extent to which the causal effect of individual offer is modified by dichotomized family offer.

(See Measures sub-section for definition of 'family offer'). In a secondary analysis, we examined heterogeneity across strata defined by ordinal family offer. We fitted a linear probability model with two-way multiplicative interaction terms encoding the extent to which the causal effect of individual offer is modified by family offer levels of zero, one, two, three, four, and five or more. We conducted a linear trend test. Finally, we conducted sensitivity analyses which we report in a supplementary note.

Models were fitted using robust standard errors, accounting for clustering at the community level. We did not formally adjust for multiple testing as we conducted only twothree hypothesis tests. Analysis was conducted by KM.

Missing Data

We conducted a complete case analysis as only 10/15,675 observations had missing outcome data. All other variables included in ~~the analysis~~regression models were complete.

Power and Sample Size

The HITS sample size was calculated to detect a relative reduction of 25% or more in HIV incidence among females aged 15 to 30 with power exceeding 80% and $\alpha = 0.05$. Further details have been previously reported [~~12~~19].

Ethics Statement

The Biomedical Research Ethics Committee of the University of KwaZulu-Natal approved study protocols for the AHRI's population-based HIV testing platform and HITS intervention (BE290/16 and BFC398/16) [12,19].

Role of the funding source

Study sponsors had no role in the design, data collection, analysis, interpretation, or write-up of this study, nor did they influence the decisions to submit the results for publication.

Conflicts of interest

The authors declare no conflicts of interest relating to this manuscript.

Results

Participants and Network

Of 37,068 residents who met inclusion criteria for the HITS study, 15,675 participated and 15,665 were included in the analysis (see Figure 1). 5638 participants lived in intervention communities (i.e. communities to whom an incentive was offered) and 10,037 in control communities. Further descriptive results have been previously reported [12].

It was common for participants to have family members in different households (60.4%, 9,468/15,675) and different communities (42.2%, 6,613/15,675) (see Table 1). However, compared to people living in control communities, people in intervention communities were more likely to have family members who live in an intervention community (85.1%, 4,799/5,638 vs. 9.4%, 945/10,037). This is because family member households are geographically clustered. Study arms were balanced on age, gender, HIV testing history, network size, and proportions of family members in different households and different communities.

Each community had family connections with almost every other community (see Figure 2). Overall, 77% (83,368/107,746) of connections were within communities (as opposed to across them). On average, communities in the control arm had 1947 (56,459/29) connections to individuals in other control communities whereas communities in the intervention arm had an average of 1682 (26,909/16) connections with individuals in other intervention communities. The proportion of connections that spanned intervention arms was 52% (11,178/ 21,507) for control communities and 80% (11,178/14,049) for intervention communities.

Two-thirds (64.7%, 3,647/5,637) of participants in the intervention arm agreed to take an HIV rapid test whereas half (50.7%, 5,087/10,028) of participants in the control arm agreed, leading to an overall risk difference of 13.6 (95% CI: 12.0 to 15.3). Of the 8734 participants who consented for an HIV test, HIV test results were recorded for 8700.

Primary Analysis

We found support for the hypothesis that the effect of the incentive on an individual's HIV testing uptake is augmented by offering incentives to their family members prior to, or at the same time as, them (See Figure 3). Among participants with at least one family member who was offered the incentive, the micro-incentive increased testing uptake by 21% (95% CI: 19.9 to 22.3~~, P<0.001~~). In contrast, among participants with no family members who were offered the incentive, the micro-incentive only increased testing uptake by 6.5% (95% CI: 5.3 to 7.7~~, P<0.001~~). The risk difference among the former group is 14.6% higher (95% CI: 9.3 to 19.9~~, P<0.001~~) that among the latter.

Secondary Analysis

The strength of the effect of the individual offer increased as more family members received a prior or contemporaneous offer of the incentive, further supporting the main hypothesis. Effect sizes increased from 6.5% (95% CI: 5.3-7.7~~, P<0.001~~) among participants with no family members who received the offer to 26.3% (95% CI: 23.5-29.0~~, P<0.001~~) among participants with three family members who received it. The effect size of the individual incentive appeared not to change substantially when four (RD: 25.5, 95% CI: 20.2-30.7~~, P<0.001~~) or five or more (RD: 24.8, 95% CI: 20.7-28.9~~, P<0.001~~) family members received the offer. A linear trend test showed that for each additional family member who was offered the incentive, the risk difference for the effect of the incentive on testing uptake increased by 4.8% (95% CI 2.4 to 7.2~~, P<0.001~~) on average.

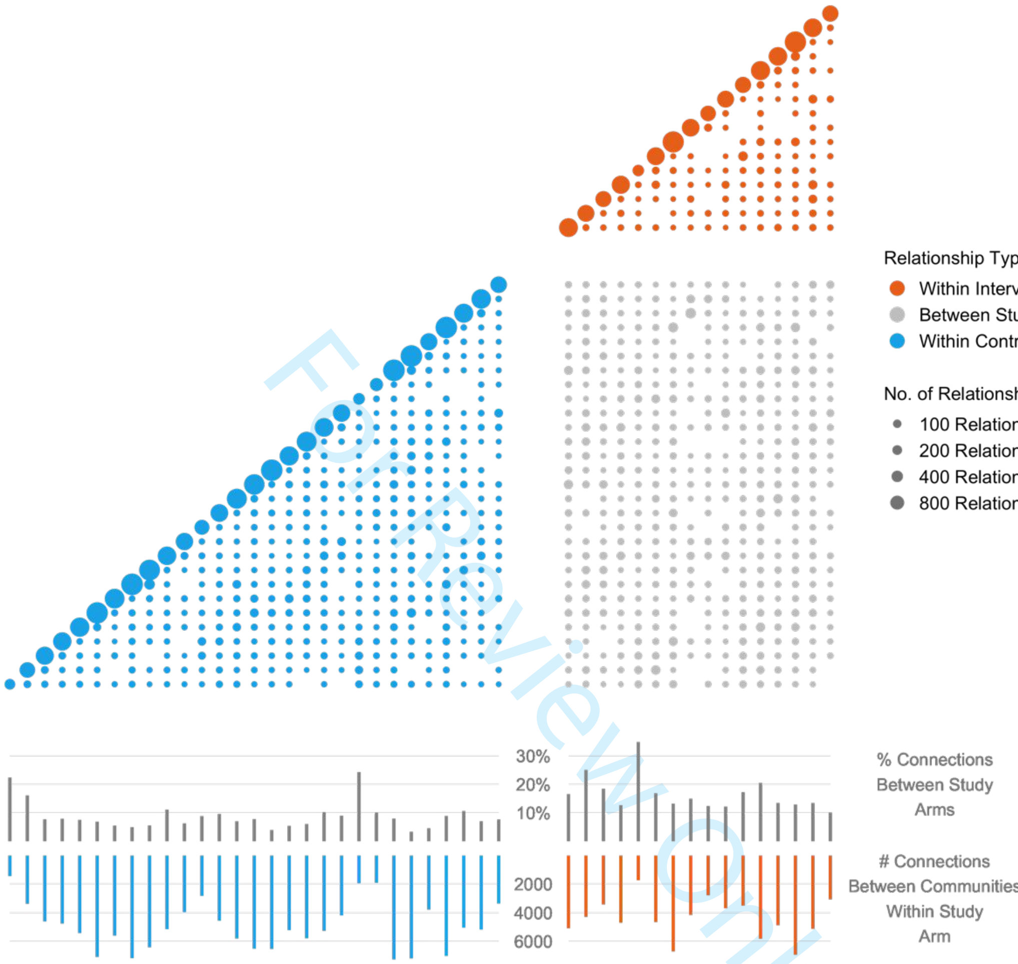

Figure 2: Family connections between communities in HITS study

The top part of the figure is a grid showing the number of family connections within each of the 45 randomization communities on the diagonal, and the number of family connections between each pair of communities below the diagonal. The size of the circles is proportional to the number of connections. Orange and blue bar graphs in the lower part of the diagram show the number connections across communities but within the intervention arm and control arm, respectively. The grey bar graph shows the proportion of connections across communities in different study arms. The diagram shows that each community was connected to almost every other community through family ties.

Subgroup	Control Clusters	Intervention Clusters	Efficacy (95% CI), P Value
	% (n/N)		
Dichotomized Family Treatment			
0	51 (4608/9029)	57·5 (775/1347)	6·5 (5·3 to 7·7), P<0·001
1+	45·6 (242/531)	66·6 (2695/4044)	21·1 (19·9 to 22·3), P<0·001
Ordinal Family Treatment			
0	51 (4608/9029)	57·5 (775/1347)	6·5 (5·3 to 7·7), P<0·001
1	46·5 (159/342)	64·2 (981/1528)	17·7 (16·3 to 19·1), P<0·001
2	45·4 (49/108)	69 (705/1021)	23·7 (21·7 to 25·7), P<0·001
3	42·5 (17/40)	68·8 (460/669)	26·3 (23·5 to 29), P<0·001
4	42·1 (8/19)	67·6 (225/333)	25·5 (20·2 to 30·7), P<0·001
5+	40·9 (9/22)	65·7 (324/493)	24·8 (20·7 to 28·9), P<0·001

Plot of Efficacy (95% CI)

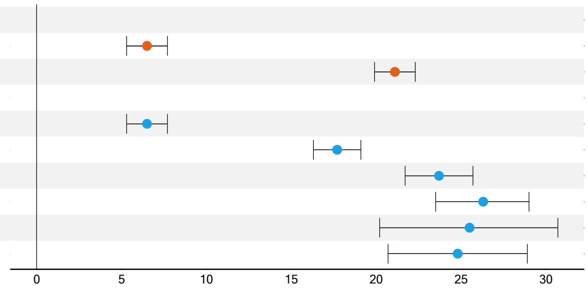

Figure 3: Effect Heterogeneity of HITS Intervention
The table shows results from the primary analysis (dichotomized family treatment) above and the secondary analysis (ordinal family treatment) below. Efficacy was calculated on the risk difference scale.

Discussion

The HITS study confirms that a modest community-wide financial incentive increases ~~the~~ uptake of HIV testing. Our study establishes that an individual offered a financial incentive is more likely to take up ~~HIV~~ testing when family members have received the same offer prior to~~,~~ or at the same time as~~,~~ them. The strength of the effect appears to increase with the count of family members in receipt of the offer.

~~Randomized~~This finding adds to a growing body of evidence from randomized control trials ~~have consistently demonstrated positive effects of~~ demonstrating that economic incentives ~~on~~ increase the uptake of HIV testing ~~among direct recipients [12–~~[8,13,14~~]. Some~~,20–24] and improve clinical cascade outcomes more generally [25]. Past trials show consistent evidence that incentives improve treatment initiation [26,27], adherence to ART [22,28–32], and continuation in care [27,30]. They show mixed evidence that incentives improve linkage to care [26,27,33]. Despite their promise as a general-purpose HIV intervention, however, economic incentives have not been shown to lead to substantial reductions in incidence [34].

Though prior studies are often not explicit about the causal mechanism through which incentives are hypothesized to shape behavior, several explanations do appear in epidemiologic literature. Incentives can change the structural environment in which behavior unfolds (for instance, by alleviating poverty); they can affect the price of some behavior or good, or the income of the recipient in relation to that good or behavior; and they can intervene on the psychological processes that shape behavior [35,36]. In each case, studies commonly assume that the causal chain unfolds entirely *within* individuals and not across them.

There are some notable exceptions. Several trials have shown that incentivizing close social contacts – most commonly romantic [~~19~~37,38] or sexual partners [~~20,21~~39,40] or caregivers of children [~~22,23] – increases~~21,41] – improves testing uptake. ~~Even~~Furthermore, even in the absence of financial incentives, sexual and romantic partnerships have proven a useful conduit through which to ~~reach people at high risk for~~deliver HIV ~~acquisition with~~ testing services [9–

11]. Our study extends these findings to ~~include~~demonstrate the impact of members of the family network in general, ~~highlighting~~suggesting an opportunity to use a wider range of meaningful social relationships to reach ~~people~~individuals living with HIV with testing and other services.

~~We contribute experimental evidence to~~Developing and applying theory that reflects the ~~study~~interdependence of ~~"social contagion" [24], showing that~~ individuals could enable the ~~engagement~~development of ~~family members improves effectiveness for a large-scale health intervention targeting individual behavior. This has implications not only for the HIV response, but responses to other public health threats. Notably, it suggests an intervention modality for improving the uptake of discrete~~new interventions ~~such as COVID-19 vaccination.~~

~~Family~~. For instance, family-based intervention strategies ~~could be useful for young people with~~might be effective at reaching groups which otherwise have low access to health services~~.~~, such as young people [17,~~25~~42]. Because of high youth unemployment in South Africa [17,18], young people~~, whether minors or young adults,~~ tend to depend on family members for material support [~~26~~43]. They are likely to be connected with, and therefore reachable through, members of their family networks. ~~It should be investigated whether these connections can be used to improve service utilization among this group.~~ To apply a behavioral economics analysis to this type of intervention, it would be useful to define the concepts of *utility* and *resources* at the group level, to understand decision-making as a collective (rather than individual) process, and to understand the impact of cognitive biases on this collective process.

We make a novel ~~methodological contributions~~contribution to the fields of study design and applied causal inference. ~~For the first time, we~~Our results show empirical evidence for the violation of the assumption of "partial interference" in the context of a large-scale cluster-randomized trial [~~27~~44]. The assumption holds that while individuals within clusters might influence each other's outcomes, individuals across distinct clusters do not. It underpins the interpretation of the difference in average outcomes (comparing intervention and control arms) as an overall treatment effect [~~27~~44]. When there are substantial connections across clusters, failing to account for them might lead to biased or uninterpretable effect estimates.

~~A limitation of our study~~It is likely that there are important social relationships that are relevant to HIV testing that were not captured in population surveillance data~~ that are likely relevant to HIV testing. These include non-kin relationships among residents of the surveillance area and all relationships between residents and non-residents.~~. This is a limitation of our study. Further research should ~~identify and measure these relationships and~~ develop methods to account for missing network data and design new approaches to measuring sociocentric networks. A further limitation is that we used the assumption of partial interference to calculate standard errors, though we show this assumption to be violated. This was motivated by the fact that network connections are much denser within clusters than they are across them; we do not expect this analytic decision to lead to anti-conservative estimates of uncertainty. Finally, we did not adjust for multiple testing, though we note that using the Bonferroni correction (i.e. using a nominal Type I error rate of 0.05/~~2~~3 = 0.~~025~~017) would not have altered the main conclusions of this study.

~~Because the study intervention was randomly assigned after the formation of family relationships, a~~A major strength of our findings is that they are not susceptible to homophily bias – bias that arises because of the tendency for people with similar unmeasured characteristics to form relationships based on those characteristics [~~28].~~45]. This is because the study intervention was randomly assigned after the formation of family relationships. A further strength is the applicability of our approach in different settings~~;~~: it is feasible to conduct ~~similar analyses for studies~~a family network analysis using data from any study embedded in ~~other~~the health and demographic surveillance systems ~~in~~of South Africa. Finally, sensitivity analyses show the estimates presented in the main analysis to be conservative.

~~For the field of public health to meet the health challenges of our time, it is crucial to use the best available data and analyses to inform policies and programs. Yet the field has not fully exploited recent advancements in the collection and analysis of data, including social network data. Eric Schmidt, a former CEO of Google, famously quipped that humans created as much data in two days in 2010 as we did between the dawn of civilization and 2003 [29]. These data are largely~~

held by private companies which have gained and monetized ever more granular insights about how human relationships structure human behavior. In just the final quarter of 2021, Facebook's parent company received $33 billion in proceeds from advertising [30] – a ubiquitous and effective behavioral intervention.

The benefit of understandingUnderstanding humans in the context of their relationships should not only be realized in shareholder profits, but in can lead to improvements toin population health. There is an urgent need to cultivate robust social network data for epidemiologic analysis – whether by collecting them, constructing them from already collected study data as we did here, or connecting passively collected information, such as social media data, with large public health datasets.

Conclusion

Conclusions

By combining family network data with data from a field experiment, we showed that network-based financial incentive programs for a behavioral health intervention might be more efficient than individual-based programs. Future HIV testing studies should assess interventions targeted at networks. More generally, public health studies should leverage data on participants' social networks to generate new insights about population health and to spur on the development of new intervention approaches.

Data Sharing Statement

Study data, including deidentified participant data and data dictionaries, are available for download from the AHRI Data Repository (https://data.ahri.org/index.php/home) subject to the submission and approval of a study proposal.

Author Contributions

KM conducted analysis and drafted manuscript. ETT, MTB, LB edited manuscript. KM developed analytic plan with ETT, HYK, and TB. FT and TB accessed and verified all underlying data. All authors discussed and reviewed manuscript.

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Table 1: Baseline Characteristics

	Control Arm (N=10037)	Incentive Arm (N=5638)	Overall (N=15675)
Age			
15-25	3920 (39.1%)	2292 (40.7%)	6212 (39.6%)
26-35	1690 (16.8%)	922 (16.4%)	2612 (16.7%)
36-45	1194 (11.9%)	679 (12.0%)	1873 (11.9%)
46-55	1247 (12.4%)	695 (12.3%)	1942 (12.4%)
>55	1986 (19.8%)	1050 (18.6%)	3036 (19.4%)
Gender			
Female	6974 (69.5%)	3829 (67.9%)	10803 (68.9%)
Male	3063 (30.5%)	1809 (32.1%)	4872 (31.1%)
Ever Tested HIV+			
Yes	1796 (17.9%)	1029 (18.3%)	2825 (18.0%)
No	6344 (63.2%)	3716 (65.9%)	10060 (64.2%)
Refused	113 (1.1%)	61 (1.1%)	174 (1.1%)
Missing	1784 (17.8%)	832 (14.8%)	2616 (16.7%)
Family Network Size			
0	290 (2.9%)	134 (2.4%)	424 (2.7%)
1-5	5365 (53.5%)	3029 (53.7%)	8394 (53.6%)
6-10	3064 (30.5%)	1723 (30.6%)	4787 (30.5%)
11-15	961 (9.6%)	539 (9.6%)	1500 (9.6%)
16+	357 (3.6%)	213 (3.8%)	570 (3.6%)
Percentage of Family Members in Different Household			
0%	3990 (39.8%)	2217 (39.3%)	6207 (39.6%)
0-20%	820 (8.2%)	438 (7.8%)	1258 (8.0%)
20-40%	1484 (14.8%)	909 (16.1%)	2393 (15.3%)
40-60%	1390 (13.8%)	792 (14.0%)	2182 (13.9%)
60-80%	1343 (13.4%)	727 (12.9%)	2070 (13.2%)
80-100%	571 (5.7%)	313 (5.6%)	884 (5.6%)
100%	439 (4.4%)	242 (4.3%)	681 (4.3%)
Percentage of Family Members in Different Community			
0%	5831 (58.1%)	3231 (57.3%)	9062 (57.8%)
0-20%	1237 (12.3%)	655 (11.6%)	1892 (12.1%)

	Control Arm (N=10037)	Incentive Arm (N=5638)	Overall (N=15675)
20-40%	1269 (12.6%)	759 (13.5%)	2028 (12.9%)
40-60%	803 (8.0%)	486 (8.6%)	1289 (8.2%)
60-80%	537 (5.4%)	320 (5.7%)	857 (5.5%)
80-100%	189 (1.9%)	88 (1.6%)	277 (1.8%)
100%	171 (1.7%)	99 (1.8%)	270 (1.7%)
Network Treatment (# Family Members in Incentive Arm and who have Prior Study Visit)			
0	9092 (90.6%)	839 (14.9%)	9931 (63.4%)
1	551 (5.5%)	1205 (21.4%)	1756 (11.2%)
2	175 (1.7%)	1088 (19.3%)	1263 (8.1%)
3	77 (0.8%)	810 (14.4%)	887 (5.7%)
4	50 (0.5%)	570 (10.1%)	620 (4.0%)
5+	92 (0.9%)	1126 (20.0%)	1218 (7.8%)