Assessing Opportunities for Solar Lanterns to Improve Educational Outcomes in Off-Grid Rural Areas: Results from a Randomized Controlled Trial

Ognen Stojanovski (ognen@stanford.edu)
Program on Energy and Sustainable Development (PESD),
Stanford University

Mark Thurber (mthurber@stanford.edu)
PESD, Stanford University

Frank A. Wolak (wolak@stanford.edu)
PESD and Department of Economics, Stanford University

George Muwowo (muwowog@yahoo.co.uk)
Affiliated Researcher, PESD

Kat Harrison (kharrison@acumen.org)
Acumen

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ABSTRACT

Solar lanterns are promoted across rural Sub-Saharan Africa to improve educational outcomes. We undertake a randomized controlled trial in Zimba District, Zambia to evaluate whether solar lanterns help children study and improve academic performance. The research design accounts for potential income effects from receiving a lantern and also "blinds" participants to the study's purpose. We find no evidence that receipt of a solar lantern improved performance on key examinations. We also do not observe impacts on self-reported study habits. Additionally, a cost-effectiveness analysis suggests that solar lanterns are not a promising way to improve educational outcomes in developing countries relative to other available options. Several features that likely exist in other developing regions appear to drive our results. First, flashlights are now the dominant lighting source in rural Zambia, so solar lanterns may have only limited appeal for prospective users that no longer rely on traditional options like kerosene lamps. Second, improved energy access--whether through solar lanterns or otherwise--is likely a relatively unimportant educational input in settings like Zimba.

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Corresponding author: Ognen Stojanovski, PESD, Stanford, CA, ognen@stanford.edu

1. Introduction and Motivation

Rural areas of Sub-Saharan Africa, where children lack access to high-quality educational opportunities, tend to also be energy poor. As a result, solar lanterns[1] have been promoted across the region as a promising first step toward improving both lighting in homes and educational outcomes (IEA 2017). Since 2010, manufacturers and distributors have sold over 15 million solar lanterns to rural households throughout Sub-Saharan Africa (GOGLA 2017). The potential educational benefits of these lights have been extensively highlighted. While planning fieldwork for this project in 2015, we identified 110 companies active in the sale, distribution, or manufacturing of solar lights in Sub-Saharan Africa. Reviews of their websites revealed that 40 of them highlighted education-related services as a benefit of their products, while an additional 16 mentioned positive education outcomes in supporting case studies.[2] Commercial vendors of solar lanterns receive significant financial and policy support from governments, development agencies and other impact-oriented stakeholders and so promotional materials that suggest the lanterns improve children's schooling are commonplace.

However, the evidence base for the educational benefits of solar lights is quite limited. This paper addresses that gap through a randomized controlled trial (RCT) that investigates whether giving solar lanterns to children in off-grid areas of Sub-Saharan Africa results in more effective studying and improved academic performance. The experiment took place in rural Zambia and was designed to tease out the impacts of the lighting attribute of the solar lantern "treatment" from several other interventions of a comparable monetary value. (This multi-

[1] These are stand-alone lamps where a single LED light bulb is powered by an attached photovoltaic (PV) solar panel, typically rated at less than 10 Watts. The lanterns usually require five to ten hours of sunlight exposure to charge a built-in battery and then provide between three to twenty hours of light from that single charge, depending on the brightness setting of the LED bulb.

[2] For example, the website of one of the most successful solar lantern vendors declares: "This easy-to-use solar-powered light enables children across the developing world to study during evening hours, improving their grades and creating a brighter future. Parents love the affordability, reliability and opportunity it provides" (D.light (2017)).

treatment design helped avoid measuring the "income effect" of having received something worth a certain amount of money rather than the effect of owning a solar-powered lighting source). We explore the impacts of solar lighting on standardized examination scores and self-reported study habits—who children study with, where they study, and the time of day that they study—but fail to detect evidence that the lanterns affected these outcomes. We present quantitative evidence that not observing impacts of practical interest was not the result of a lack of statistical power in the research design. We also find that solar lanterns are not a cost-effective way to boost educational outcomes in developing settings relative to other available options.

We do, however, find that children in grade 7 that we randomly gave backpacks to (rather than solar lights) performed an estimated 0.3 standard deviations better on tests. This could be because backpacks might make it possible to better protect scarce school supplies and thus enable studying in the first place (as opposed to simply better illuminating an existing study environment). If the treatment effect of a solar light had been of this magnitude, our power calculation shows that we would have detected it with a more than 0.8 probability.

Despite extensive financial support for the distribution of solar lanterns on educational grounds from development agencies and others, the theoretical foundations for why these lights might be expected to improve educational outcomes are not well developed. We therefore also study the mechanisms and intermediate steps between receipt of a solar lantern, on the one hand, and improved educational performance, on the other. We do so through an analysis of detailed survey data on the daily lives of our study's participants, which we then place in context with the other literature on solar lights, as well as more broadly with other educational interventions in developing countries. This closer look reveals that solar lanterns' potential for positive educational impacts may be quite limited. Nearly all participants in our research were able to study at night even before the introduction of solar lanterns. In addition, the significant penetration of flashlights across rural Sub-Saharan Africa (the adoption and use of which has not been tracked or reported on nearly as extensively as the off-grid solar market) may further reduce the appeal of solar lanterns for populations that have already transitioned away from the traditional kerosene lamp. Finally, household poverty appears to have far greater constraints to education than inadequate lighting. Children in our study were busy with work and chores that they prioritized over school; and their families struggled to pay school fees and purchase school supplies. In places where such barriers to schooling exist, household lighting may be a relatively unimportant educational input.[3] These and other findings from our analysis likely explain why we fail to observe meaningful impacts of solar lanterns on examination scores and study habits in the RCT.

The remainder of this paper proceeds as described below. In Section 2 of this paper, we summarize the prior literature and provide more context for our study in Zambia. Section 3 details our research design, while Section 4 summarizes our empirical strategy. We present the results of the RCT through which some children were given solar lanterns in Section 5 and discuss them in Section 6. Finally, Section 7 concludes and suggests potential ways that impact-oriented stakeholders could adjust their strategies to improve positive educational impacts.

2. Solar Lanterns and Educational Outcomes: The Theory of Change and Evidence to Date

The logic underlying why solar lanterns might improve educational outcomes is that children might be able to study longer and under better conditions than traditional lights; and

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[3] There are well-documented challenges with teacher training and compensation, classroom size, lack of school supplies, nutrition, and other serious problems that hinder primary education throughout Sub-Saharan Africa (see, e.g. Lewin 2009, Hardman et al. 2011), including in regions where solar lights have been successfully sold. Whether such fundamental constraints to education mean that no amount of improved household lighting could realistically be expected to enable children to study more effectively and do better has not been closely examined.

that, in turn, might translate into better academic performance. This could come about through brighter illumination, less eye strain and fatigue, no fuel fumes, lower costs of lighting, and individualized, task-specific lighting allocated to individual users. In addition, solar lights might unlock the possibility of studying at night for children who are busy with other tasks during the day or who live far from school (Hassan and Lucchino 2016). An improved study environment at home might also help students with other at-home inputs that ultimately promote educational achievement (see, generally, Dufur et al. 2013). Moreover, if solar light ownership also somehow generates more income or free time for a household, those might then be directed toward children's education (see, generally, IEA 2017; Das et al. 2013). There could even be positive learning spillovers if children who own solar lanterns share them with classmates and thereby create a better learning environment for everyone (Gustavsson 2007). Finally, marketing and selling solar lanterns in schools through teachers may, by itself, increase the perceived returns on investment in education, thereby encouraging better outcomes (see, generally, Jensen 2010).

Despite commonplace references to such benefits of solar lighting in the off-grid solar industry, the scale and rigor of the evidence for educational impacts of solar lanterns is quite limited. A handful of studies have probed potential educational benefits, but very few have focused their inquiries on these questions. This paper is most closely related to the insightful work of Kudo et al. (2017), who undertook a similarly comprehensive RCT in rural Bangladesh. They observed short-term increases in school attendance rates by children who were given solar lanterns but no improvements in performance on annual examinations (that varied across schools and grades) or any hints of spillovers through sharing of the lights.

Other work focused on solar lanterns and education that we build upon includes Furukawa (2014) and Hassan and Lucchino (2016). Furukawa (2014) ran a small experiment in an urban setting in Uganda and observed *lower* average test scores for children who were randomly gifted a solar light relative to the control group, although he noted significant technical challenges, whereby a large portion of the lights did not work properly and may have distracted children. Hassan and Lucchino (2016) undertook a larger experiment in 13 rural Kenyan schools but failed to observe positive impacts of solar lanterns on academic performance on school-specific end of term scores in any subject except mathematics, which they recovered using a complex methodology that accounted for possible spillovers. It is not clear why mathematics might have been uniquely impacted among the many other outcomes that were tracked.[4]. This study also reported significant sharing of the lights between their treatment and control groups.

Our study is also informed by and benefits from the studies undertaken by Grimm et al. (2016), Gustavsson (2007), and Lee et al. (2018). Grimm et al. (2016) ran an experiment on the broader household-level social impacts of solar lanterns in Rwanda. They reported children shifting studying from daylight hours to after dark. But they did not detect sharing of the lights, nor did they track academic performance. Meanwhile, Gustavsson's (2007) work on solar home systems was one of the first to explore the potential educational benefits of solar lighting. He cautions, however, that children in his study who had access to such lights tended to have parents who worked as teachers, thus making it difficult to infer cause and effect relationships with grades. Finally, the more recent work of Lee et al. (2018) presents experimental evidence that energy access initiatives in rural Kenya targeting energy poverty do not result in broader poverty relief, including on educational metrics they tracked by administering a test they created.

The research presented in this paper is a field experiment investigating the relationship between access to solar lanterns, on the one hand, and academic performance and study habits,

[4] The authors did not appear to use Bonferroni corrections for the sizes of the many individual tests they ran to account for the fact that they performed multiple hypothesis tests.

on the other. It is among the largest studies of its kind in Sub-Saharan Africa and additionally benefits from having a direct and credible measure of academic performance – a mandatory standardized examination that was administered equally across all subjects in our study (as well as the entire population they were drawn from) and for which the subjects would have been highly motivated to do well on even if our research had never taken place. In addition, the administration of the experiment's treatment was designed to tease out the impact of receiving the lighting attribute of solar lanterns, as opposed to an income effect or other mechanisms that might be triggered by being given a lantern. Finally, we focused on avoiding potential sources of contamination by "blinding" participants to the purpose of the research, undertaking it in an area where solar lanterns were not otherwise readily available, and not drawing undue attention to the lights' hoped-for benefits (but while still encouraging children in the treatment group to use them). These features of our experimental design, as well as an accompanying rich survey dataset, enable us to determine not just whether solar light ownership impacted educational outcomes of interest, but also to examine why we may have observed our results. That allows us to better develop the theoretical underpinnings for whether solar lights might be good candidates to improve educational outcomes in developing country settings, and to directly compare our results with other education-oriented RCTs.

3. Research Design and Implementation

The primary research question for this study was whether giving children solar lights would improve academic performance. We prioritized introducing the solar lanterns in a similar manner to how they would be distributed outside of a research setting, which is typically the sale of lights by a social enterprise. We also required a rural location similar to other places in Sub-Saharan Africa where solar lanterns had successfully been sold, but one where such lights had not yet actually been widely promoted or offered for sale. That way we could minimize the risk of contamination from participants' exposure to solar lanterns outside our research. In addition, we wanted to recruit participants that would plausibly be motivated to use solar lanterns to study in order to improve academic performance.

Zambia's Zimba District met all these requirements. Zambia is a country where, until recently, there were few options for lighting homes in off-grid areas. Although its solar sector is active, it is relatively new and underdeveloped compared to countries like Kenya and Uganda, thus lowering contamination risks. Nevertheless, the demand for solar lanterns in rural regions of Zambia appears to be as strong as in the rest of Sub-Saharan Africa. Zimba District is located in the country's Southern Province and has a similar profile to a number of nearby districts where SolarAid—Africa's largest and most prominent distributor of solar lanterns—has successfully sold lights. SolarAid's distribution model is designed to sell lights through schools and, in 2015, the enterprise identified Zimba District as a promising location where lights would soon be sold. However, in the interest of supporting this research, SolarAid agreed not to enter the district until after data collection for this study was complete.

In addition, the Zambian government has previously invested in multiple projects to provide solar lighting to rural schools and households (see e.g. Gustavsson 2007), including in Zimba District. While these projects have focused on larger solar solutions that can electrify an entire structure rather than the individual task-specific solar lanterns we study here, they are indicative of the broader perception that rural Zambia is a place where solar-powered lighting might deliver meaningful educational benefits.

We focused the research on students in grades 7 through 9—the last three grades of primary school in Zambia—for several reasons. First, children in earlier grades would likely have been too young to be able to answer the questions in our surveys. Second, our scoping research revealed that lower grades were generally not assigned much homework, making it less likely that improved lighting would influence studies and performance. Third, school officials pointed out that it is mostly grade 7 and beyond when children drop out of school altogether, so interventions that might improve performance and encourage ongoing enrollment might be particularly well targeted to those grades.

Most importantly, children in grades 7 and 9 take standardized national examinations. It is widely believed that students across Zambia—as well as their parents and teachers—are aware of the importance of these tests and take them seriously. In particular, scoring well on the grade 9 examination is most often the only hope students from poor rural areas have to enroll in secondary school and continue their education. Children in those two grades are focused on preparing for the examinations, especially during the months of September, October and November. Overall, these tests met our research design requirements, as we could plausibly assume that children would be quite motivated to use all tools at their disposal—including, potentially, solar lanterns—to improve performance. Moreover, the fact that the examinations are standardized and graded on a national level without differences between schools and classrooms makes them an ideal way to measure academic performance outcomes in an RCT.[5]

We carried out the RCT in 12 government-run primary schools, randomly selected from a master file of all schools in Zimba District.[6] A team of researchers then conducted fair lotteries at each school. These lotteries were the delivery mechanism for the RCT's different

[5] Zambian children must do well on these examinations in order to continue their studies. Although any standardized test could be criticized as measuring how well a student is able to take the test itself rather than being a measure of learning, the Zambian national examinations are nevertheless crucial for further educational attainment, especially in rural areas. This makes them an important and useful real-world educational outcome to track in research.

[6] Zimba District's schools are spaced over a large rural area, with direct-route distances from the district's central educational offices ranging from 0.5km to 160km. When accessing schools, distance is only part of the equation, since travel to even relatively nearby schools is often heavily impaired by poor road quality or rains.

"treatments", including the giving away of over 200 solar lanterns to randomly selected children. The lotteries took place at the start of the second school term in May 2016, were designed to isolate the impact of solar lighting, and are more fully detailed in Section 3.1 below. The national examinations were administered six months later and we collected student scores directly from Zambian education officials in early 2017.

We also asked students to complete detailed baseline and endline surveys. Over 1,400 children in grades 7, 8 and 9 took in-school surveys at the start of the school year in February 2016, as well as during the national examinations season in October and November 2016. Not all children attend school every day but 80% of children who filled out the October survey were matched to having also completed the baseline one. The student surveys took about one hour to complete and were conducted by a different team of researchers from the ones that handed out solar lights and other lottery "prizes" in the middle of the school year.

We collected the survey data for several reasons. First, we were interested in detecting impacts of solar lanterns on certain study habits irrespective of examination performance. In other words, the times of day that children study, study locations, study partners, and types of lights used for nighttime studies were additional outcomes of interest in our RCT. Second, having this additional data enabled us to control for background variables and potentially obtain more precise estimates of the impacts of solar lights.

Third, the surveys helped us achieve additional research objectives, namely examining the mechanisms through which solar lights are introduced and used. Simply estimating the average impact of handing out lights does not provide information about whether and how students actually use the lights. Fourth, making the surveys broad in scope helped us blind participants to the study's goals. We did not want students to feel that there were "correct answers" when it came to reporting study habits, the use of solar lanterns and, most importantly, the relationship between the two.

Finally, the rich survey dataset we ended up with covered many aspects of students' daily lives and enabled us to gain important insights into the broader educational environment into which solar lanterns are deployed. We can therefore examine why we failed to observe impacts. Ultimately, this broader examination of the relationships between household energy access, poverty, and children's academic opportunities is key to understanding if and how improved household lighting might translate to improved educational outcomes.

Table 1 summarizes the research design. Additional details on the collected data and RCT participation rates are included in Appendix 2.

Table 1: Research Design Summary

Location	Zimba District, Zambia
Subjects	Students in grades 7-9 in 12 randomly-selected schools
RCT Treatment Definition	Gift of a solar lantern to a student (see Section 3.1)
RCT Outcomes	(1) National examination scores (grades 7 & 9 only) (2) Study habits (a) most used lights for studying in dark (b) most frequent time of day for studying (c) most frequent study location (d) most frequent study partner (if any)
Data collection summary	
Baseline surveys completed (February 2016)	1588 (36% grade 7, 35% grade 8, 29% grade 9)
Endline surveys completed (October 2016)	1409 (37% grade 7, 34% grade 8, 29% grade 9)
*Number of matched baseline-endline pairs**	1122 (80% of endline surveys)
Median age of those completing both surveys	15 (15 grade 7, 15 grade 8, 16 grade 9)
Gender ratio of those completing both surveys	47% girls (51% grade 7, 48% grade 8, 41% grade 9)
Number of participants in RCT lottery (May 2016)	1211 (76% of baseline survey participants, 86% of endline survey participants)

* It is likely that more students completed both of our surveys but their two surveys were not confirmed as a match. The manual matching process was labor and time intensive and we prioritized avoiding false matches at the expense of leaving out likely matches.

3.1 RCT Treatment Implementation

The priority for our experiment's implementation was ensuring that any given student within a grade at a particular school had an equal and random chance of being "treated". To do that, we conducted a series of 36 lotteries – one for each grade level at all 12 schools. Because not all children attend school every day, only those that both took the baseline survey *and* were present on the day of the lottery several months later were eligible to participate. Therefore, children that missed school during either of the two surveys or the lottery are left out of the RCT's final sample for analysis.

We took precautions to ensure that the lotteries were *not* perceived as solar lantern giveaways. Instead, the goal was for school officials, teachers, students, parents, and even some of our own researchers to perceive the lottery as an exercise intended to thank children for participating in a general study of Zambian schooling.[7] We therefore also gave away three other prizes or "treatments": backpacks, battery-powered alarm clocks, and soap. The "control" students received a candy. There was no general emphasis on the lanterns; they were just one of several prizes that students were eligible to win thanks to completing broad surveys about their daily lives. The lottery details are summarized in Table A5 of Appendix 3.[8]

This approach enabled us to deliver the lights in an educational setting and encourage students to use them, but at the same time hopefully avoid giving cues about any particular impacts we "wanted," which could have resulted in data bias (or even potentially favorable treatment towards certain students). Another benefit of awarding multiple prizes was that it

[7] Although students, teachers and school officials in Zimba District were not aware of the solar lantern focus of the study, provincial and national education officials were fully informed of the research design.

[8] In each school, approximately half of the students participating in the lottery won a prize (solar lantern or one of three alternatives), while the other half received candy as a consolation prize. In schools where we awarded a sizeable number of lights, we only gave away two of the three other possible prizes. That way we minimized giving out very few of any particular prize and thereby hopefully lowered the risk of students ranking the relative importance of the different prizes.

enabled us to have a consistent approach with the "pure control" schools where no students received lights. By also awarding prizes in those schools, we avoided the political and practical risks of control schools being perceived as different from the 9 "treated" ones.

Nevertheless, because solar lanterns were likely not as familiar to the children as the other prizes, we did take limited additional measures when handing them out. Lantern winners received an "information card" – a brief, easy-to-understand sheet (printed on high-quality cardstock) that consisted of instructions on proper use, emphasized that the lantern could be helpful for studying, and provided a number to call in case it stopped working (see Appendix 3). Research staff also demonstrated how to use the light and delivered the same messages from the information card verbally when giving a child a lantern. In this regard, we mimicked what a vendor might do when selling a solar lantern while still not drawing too much attention to the lights being somehow more special than the other prizes. Finally, we sent one research team member back to the schools on four occasions to check whether students who had won a light still owned it and were using it. This was presented to participants as a routine part of warranty support for the lanterns by their distributor.

4. Empirical Strategy

4.1 Treatment Definition and ATE Interpretation

The key objective for this study was to detect impacts solar lanterns may have on educational performance, specifically on the grade 7 and 9 national examinations that are a key component of the Zambian schooling system. Although we awarded solar lanterns to randomly-selected students, we could not guarantee that the children would *use* the lanterns. Instead, we could only *give* students a light and *encourage* them to use it for studies. Thus, we estimate average treatment effects (ATE) for the treatment of randomly having been given a light (or another prize), which is conceptually equivalent to an intent-to-treat effect if we the treatment were to be defined as using the lights for studies.

Moreover, giving out multiple prizes rather than just solar lanterns enabled us to isolate the solar-powered lighting attribute of our target intervention and thereby control for any income effects that might have been triggered by the receipt of a solar lantern. The other prizes we handed out were worth approximately the same as the retail price of a solar lantern and, in some cases, could also be considered helpful for education. We could therefore more credibly claim that the ATE estimate for the solar lantern treatment group is estimating the impact of receiving a lighting product, distinct from the impact of receiving something that is worth approximately USD 10 and that could potentially be monetized and repurposed.[9] We note, also, that we did not observe any evidence that any of the prizes were monetized, repurposed, traded or otherwise not used for their intended purpose. During the endline survey, 93% of backpack recipients and 87% of both solar lantern and clock recipients reported still owning the prizes they won in the lottery.[10] Importantly, very few children reported having sold or given away their prize (Table 2). We therefore believe that we were successful in implementing a research design with the goal of studying the impact of having received a product with solar-powered lighting attributes (as opposed to the impact of having been gifted something worth a certain monetary amount).

Table 2: RCT "Treatment Lottery" – Reported Status of Awarded Prizes at Endline

Endline Status	**Prize**				
	Solar Lantern	***Backpack***	***Alarm Clock***	***Soap***	***Candy (control)***
still own prize	87%	93%	87%	2%	3%
prize has been used up	4%	6%	6%	90%	94%
sold or gifted prize	1%	4%	1%	1%	1%

[9] An additional advantage was that the other three prizes were familiar items that children would have been aware are valuable and not normally given away. They were therefore useful to signal the value of solar lanterns to children that might not have previously been exposed to solar lights (or may possibly have viewed them as free goods that charities hand out).

[10] In contrast, over 90% of the soap and control (candy) groups – prizes that we expected to be consumed – did, indeed, report that they had consumed their prize.

4.2 Sample Balance and Attrition

To test the assumption of successful randomization, we undertake a covariate analysis to check for imbalance between the different experimental groups *prior* to the treatment. The data we collected prior to implementing the treatments (primarily through the detailed baseline surveys students filled out) does not reveal any obvious imbalances with respect to covariates we hypothesized would be predictive of the outcomes, namely student's age, gender, and poverty index, as well as their self-reported comfort with the English language (which is the language of the examination). As shown in Appendix 2, none of these covariates vary significantly between the different experimental groups. We also regress the assignment to the different experimental groups on all of the covariates. Tests of joint significance do not offer evidence against the null hypothesis that these covariates do not predict treatment assignment more than would be expected by chance alone. Finally, our field work team did not experience any logistical or political problems in our ability to run fair lotteries in the schools. We therefore believe that the assumption of a successful randomization is well supported.

In addition, we need to also assume that the final dataset does not reflect systematically different attrition rates from the study. We note that overall attrition rates in the study were quite low and we successfully matched 80% of children who completed an endline survey to a completed baseline survey. Of those in grades 7 and 9, we matched a further 80% to an examination score provided by school authorities. It should be noted that many more children likely participated in both surveys and sat for the examinations. However, the matching was performed manually based on name, school, and grade level and was time and labor intensive. Many children switched between using their traditional names and English names when filling out the surveys and they were inconsistent in the spelling of their traditional names and surnames. We therefore likely left many more matches "on the table." Despite this logistical difficulty, attrition was low and there is no evidence for differing attrition rates (as measured by our ability to match baseline and end line surveys and examination scores) between our various experimental groups.

4.3 Empirical Model

In order to recover estimates of the light giveaway's impact on national examination scores, we first begin by estimating the following basic model:

<u>Model 1</u>:

$$\begin{aligned} exscore_{ij} = \alpha &+ ATE_{solar}(solar_{ij}) + ATE_{bpack}(bpack_{ij}) + ATE_{clock}(clock_{ij}) \\ &+ ATE_{soap}(soap_{ij}) + \lambda_{school,j} + \epsilon_{ij} \end{aligned}$$

The outcome variable "$exscore_{ij}$" is the examination score for student i in school j, while "*solar*", "*bpack*", "*clock*" and "*soap*", are binary (0,1) variables indicating the different treatment groups in the experiment. The parameter $\lambda_{school,j}$ is the fixed effects for school j. Finally, α is a constant, while ϵ_{ij} is a mean zero idiosyncratic component unique to any given student. It is assumed to be mean-independent of the treatments and covariates. Because the official scoring of both the grade 7 and 9 examinations is fairly complex and the absolute scores have no intuitive interpretation, we first standardized the examination score data such that both the grade 7 and grade 9 samples in our study can be interpreted as coming from a distribution with mean 0 and standard deviation 1.

Although our tests for successful randomization do not require that we control for observed covariate imbalance, we nevertheless specify two additional models where we add variables to the model in an attempt to obtain more precise estimates of the average treatment effects of having given away the various prizes. During the initial phase of the study's design, we assumed that in rural Zambia, as in most of the developing world, school performance is highly correlated with gender (with girls doing worse than boys), socioeconomics (with children from wealthier families doing better), and with student age (with older students in a class likely doing worse than younger ones, since older children are likely to have repeated grades or enrolled in school late due to other family obligations). We therefore specify a Model 2, where we add gender, age, and a socioeconomic variable to account for the covariates that we believed *ex ante* would most strongly predict performance on the Zambian examinations. Our socioeconomic variable is an index derived from the Zambia-specific Poverty Probability Index (PPI), a poverty measurement tool developed by the Grameen Foundation that uses answers about a household's characteristics and asset ownership (which we asked about in our baseline surveys) to assess the likelihood that a household is living below the poverty line (PPI 2017).

We further specify a third model (Model 3) that controls for additional variables that we believed could be predictive of examination performance. This was done in the hopes of being able to recover even more precise estimates of the impacts of handing out solar lanterns. This final specification was based on prior internal research conducted by SolarAid in rural Africa that suggested certain study habits (such as studying at night or with a friend) resulted in better academic performance. We therefore added categorical variables to account for students' self-reported study patterns, specifically which type of light they use most when studying, the time of day that they most often study, the place where they most often study, and whom they most often study with. In addition, we learned during the fieldwork scoping portion of this study—but prior to collecting any data in Zimba District or implementing the treatment—that mastery of the English language would likely be highly predictive of examination performance.[11] We therefore

[11] That is because the national examinations are administered in English, which is the official language of school instruction in grades 7 through 9, even though many children and their teachers in rural areas like Zimba District do

also added binary variables to account for students' self-reported difficulties with speaking or reading and writing in English. Models 2 and 3 were specified prior to commencing fieldwork and the covariates are pre-treatment ones collected from the baseline survey.

4.4 Defining and Evaluating Economically Meaningful Impacts

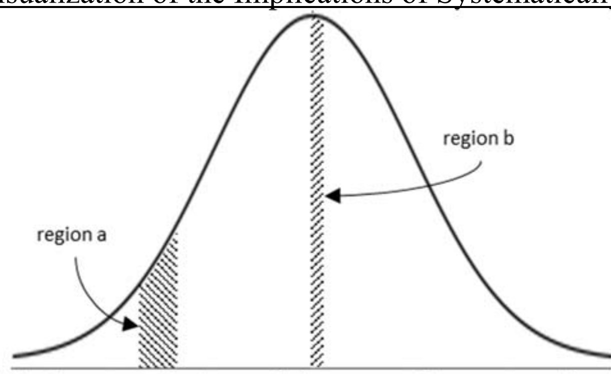
Within the literature on primary school education developing countries, interventions that result in an increase of 0.1 standard deviations on test scores are typically not considered meaningful, whereas an increase of 0.3 standard deviations or more is usually viewed as a large and meaningful effect (J-PAL 2019). Such rules of thumb from literature reviews must be taken cautiously and comparisons across studies based solely on standard deviation shifts can be challenging. Nevertheless, we believe that for our study, the impacts of solar lanterns would, indeed, need to be on the order of 0.3 standard deviations within Zimba District in order to be practically meaningful.

Impacts smaller than that may be of relatively little practical significance for children in Zimba District. That is because Zimba is a poor, rural area whose students generally perform far worse on the examinations than national averages. In 2016, the year of this study, the district ranked 94th in grade 7 and 90th in grade 9 examination performance out of 101 total educational districts in Zambia (ECZ 2017). Because the average examination scores in our research sample are systematically lower than national averages, the impacts of any intervention (solar lights, backpacks or otherwise) of magnitudes less than 0.3 standard deviations likely mean relatively little in terms of moving children higher in the national percentiles of performance. In other words, a large increase in standard deviation within our below-average sample is required in

not have a strong grasp of the language and are generally not exposed to it outside of school. Not surprisingly, prior work by the Examinations Council of Zambia had revealed that English reading proficiency is, indeed, a strong predictor of examination performance in both grades and especially grade 7 (ECZ 2012).

order for such an increase to translate into a meaningful increase in the national percentiles, as shows stylistically by the shaded regions in Figure 1. Only a large improvement in the national percentile scores would ultimately have any practical value for the real-life educational opportunities of children in Zimba District.[12]

Figure 1: Stylized Visualization of the Implications of Systematically Lower Scores in Zimba



Achieving the same national percentile improvement in exam scores (represented by the equal areas of regions a and b) requires a larger standard deviation shift in places like Zimba where mean performance is far below the national average (region a), than it does in locations where performance is close to the national mean (region b).

Beyond this general sense from both our study's context and the developing country educational literature that an increase of approximately 0.3 standard deviations would be a meaningful effect, we also undertake a cost-effectiveness analysis (CEA) in order to more precisely gauge the economic meaningfulness of our interventions. Here we follow the framework laid out by Dhaliwal et al. 2013 and J-PAL 2019, which propose the adoption of cost-effectiveness metrics as a way to better inform policy making in developing countries, especially in education. When evaluating educational interventions, a CEA is, in its simplest form, the ratio

[12] For example, a child in Zimba must not only pass the grade 9 examination, but also perform exceedingly well relative to peers, in order to have any hope of being permitted to enroll in secondary school. Yet while 49% of students in the nation passed the grade 9 examination, only 38% of students in Zimba District received a passing score (ECZ 2017; Ministry of Education 2017). Worse yet, the large and sprawling district has only one government-run secondary school, with a strictly limited number of spots, so a passing score alone is not sufficient. Instead, the threshold score necessary to enroll in grade 10 is actually much higher in lower-performing and under-resourced rural districts like Zimba than it is in cities like Lusaka that already have many other schooling advantages. As such, any educational interventions would need to have a very large impact on examination performance in order to "move the needle" in practical terms for the educational opportunities of children in Zimba.

of the estimated standard deviation improvement in test scores over the cost incurred to carry out the program; or conversely, the dollars required to achieve a given amount of “effect” on test scores (J-PAL 2019).

This is the method undertaken by Kremer et al. 2013, in their illuminating comparative analysis of 27 RCTs, all of which aimed to improve educational outcomes in the developing countries, but which varied widely in the interventions and study settings. The advantage of undertaking a CEA is the ability to summarize potentially complex programs in terms of illustrative, intuitive metrics and to then use this common measure to compare across different contexts, years, and interventions targeting the same policy goal. In Kremer et al. 2013, the common metric is the cost in dollars per additional 0.10 standard deviation gain in test scores generated by a program, which we also adopt for our CEA due to its simplicity and because it enables us to readily compare our results to the 27 educational RCTs they considered.

5. Results

5.1 No Evidence that Receiving a Solar Light Impacts Examination Scores

The abbreviated regression results for Models 1, 2 and 3 are shown in Table 3. We did not detect an impact of the solar lanterns on examination scores under any model specification. However, we do appear to detect a meaningful positive impact of backpacks on scores in grade 7. We estimate that giving a 7th grade child a backpack resulted in an average increase in performance of approximately one third of a standard deviations relative to those that did not get backpacks. However, we did not observe similar results for backpacks in the grade 9 data. The estimates of our treatments’ impacts are consistent across the three specifications (full results in Appendix 1).

While being given a solar lantern was not associated with examination performance, the other variables that we expected to be predictive of performance generally were. Girls did worse, as did the older children within the same grade level and those who came from poorer households. These associations were weaker in grade 9 compared to grade 7, possibly because many underperforming students for whom these three variables (gender, age, and poverty index) are highly predictive of scores in grade 7 would drop out of school altogether by grade 9.

As expected for the covariates in Model 3, children who reported difficulties with reading and writing in English also struggled (estimated 0.42 standard deviations worse for grade 7 and 0.19 for grade 9). However, the variables that reflected students' self-reported study habits were generally *not* associated with test scores. The pre-treatment study pattern data was collected 8 months before the examinations, so it is perhaps not surprising that how children reported studying in February was not predictive of their national examinations scores at the year's end.

Table 3: Abbreviated Regression Results (full results in Appendix 1)

	(1) Standardized Exam Score (robust SE)		(2) Stand. Exam Score (robust SE)		(3) Stand. Exam Score (robust SE)	
	Grade 7	Grade 9	Grade 7	Grade 9	Grade 7	Grade 9
Treatment						
solar light	0.13 (0.13)	-0.04 (0.12)	0.12 (0.12)	-0.03 (0.12)	0.18 (0.12)	-0.04 (0.12)
backpack	0.35 (0.14)	-0.22 (0.2)	0.35 (0.13)	-0.21 (0.19)	0.37 (0.14)	-0.12 (0.19)
clock	-0.02 (0.15)	-0.11 (0.15)	-0.07 (0.15)	-0.05 (0.15)	0.07 (0.16)	-0.09 (0.14)
soap	0.25 (0.15)	0.11 (0.13)	0.16 (0.15)	0.07 (0.13)	0.19 (0.16)	0.12 (0.14)
Gender (1 = female)			-0.24 (0.09)	-0.20 (0.09)	-0.27 (0.10)	-0.06 (0.09)
PPI (poverty index)			0.16 (0.05)	0.07 (0.04)	0.12 (0.06)	0.02 (0.05)
Age			-0.13 (0.03)	-0.08 (0.03)	-0.11 (0.03)	-0.06 (0.03)
English read/write difficulties					-0.42 (0.10)	-0.19 (0.11)
English speaking difficulties					-0.05 (0.10)	-0.12 (0.08)
Observations*	403	318	403	316	377	301

Robust (heteroscedasticity-consistent) standard errors in parentheses
**The number of observations varies across specifications because some children left certain survey questions blank, including those used as covariates in some of the models.*

5.2 Limited Impacts on Intermediate Outcomes (Study Habits or Solar Lantern Use)

Expectations that solar lights might improve academic performance are most often predicated on solar lanterns first improving the manner in which children study. Indeed, much of the literature has focused on the study habits of solar adopters because the ways in which children study might be the key intermediary outcomes through which solar lantern adoption translates into improved educational performance. We therefore investigated whether solar lanterns impacted study patterns, as it would be informative to detect potentially promising shifts in studying (even if in this study they did not then also lead to improved test scores).

We focus on four study habits that we hypothesized could plausibly change after the introduction of a new, brighter light source: the type of light children use most when they study in the dark, the time of day that they most often study, the location where they most often study, and whom they most often study with.[13] Figure A5 in Appendix 5 summarizes the responses that children who took both the baseline and endline surveys gave to the four study pattern questions.

We did not detect meaningful differences between children who received solar lanterns and the control group on these dimensions (Table 4; see also Figure A6 in Appendix 5). More broadly, none of our treatments seem to have obviously influenced the way in which children reported studying.[14] The only detectable differences is the type of light used for studies, but even this was *not* due to children in the solar lantern group using the lights we gave them to study. Instead, there was a higher reported use of *flashlights* by the solar group relative to the control (and, to a lesser extent, a reduced use of phones or a fire).[15] One theory for this observed result is that receiving a solar light may have exposed children to the desirability of LED task lights, but that flashlights ultimately proved to be a preferred way to access such lighting.[16]

Figure 2 shows that slightly less than 10% of students in each experimental group reported using solar lanterns to study. This suggests that a small minority of students had access to such lights in Zimba District from sources outside our research. Meanwhile, even the gift of a

[13] One question that we did not ask—even though it has been discussed in prior research—was how long students estimate they study. We were warned against asking about this by our enumerators and by school officials, as there was no way to ask the question without prompting children towards a socially favored response of overestimating time spent studying.
[14] Undertaking Chi-square tests of independence when considering the responses given by all treatment arms does not reveal dependencies between the study habit outcomes and our various treatments.
[15] Although 54% of the control group reported flashlights to be their primary study lights in the endline survey, an even larger proportion of the solar treatment group (62%) also reported flashlights to be their main lights. This 8 percentage point estimated impact of the solar lights on flashlight use is precisely estimated.
[16] However, we also note that students treated with a clock in our study also reported higher rates (62%) of flashlight use for studies, even though we do not have a theory for why this might be the case. So it is possible that the observed increase in flashlight use rates among two of our treatment groups was by chance rather than through any impact that the gift of a solar lanterns or alarm clocks might have triggered.

free solar lantern by our research team did *not* make a child more likely to report using it to study.[17] We further explore the relationships between the types of lights used for studies, other study patterns, and test scores in Appendix 5, where we find that a student's self-reported *use* of a solar lantern (regardless of whether or not they received one in our experiment) was not predictive of their test scores. This suggests that even if more children in our solar treatment group had used the lanterns we gave them to study, there may nevertheless not have been a further impact on academic performance.

Not only did the children in our solar treatment group fail to use the lights we gave them to study, but we also believe that the lights were generally not important to the children or to their families. Students we gave solar lanterns to did report greater rates of lantern use in their households and for their own personal use, but not necessarily for studying, than the control. As shown in Table 5, these differences between the groups are precisely estimated, so it could be argued that the receipt of a solar light caused children to be more likely to report that they or someone in their family used solar lanterns for something. However, even this predictable outcome is not meaningful in practical terms since the solar lantern use rates in both groups were so low in absolute terms (Figure 3).

One potential explanation for the surprisingly low rates of solar lantern use by our treatment group is that, within our research sample, the vast majority of children reported that flashlights were their family's primary lights (Figure 4). Only 12% reported kerosene lamps, candles, or a fire (all of which are considered poor quality, harmful to health and for which a shift to solar seems to be an obvious benefit) as their family's most-used lights in the baseline survey. Like solar lamps, flashlights also offer modern, LED-based lighting, and so students and

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[17] Despite attempts to encourage them to do so, only 10% of the children that we gave lanterns to reported solar as their most often used lighting for studying in the dark.

their families may not have perceived any additional benefits to using the solar lanterns we distributed compared to what they already had.

Table 4: Responses to Study Habits and Pearson's Chi-square Tests of Independence

	Most Common Study Light					
	Flashlight	Solar Lantern	Mobile phone	Fire	Candle	Other response
Control	226	36	34	44	37	40
Solar lantern	115	19	8	7	20	17
	χ-squared test statistic = 11.935, df = 5, p-value = 0.036					

	Most Common Time for Studies			
	After School (before dark)	Evening (after dark)	Late night	Other response
Control	168	111	100	37
Solar lantern	68	60	45	12
	χ-squared test statistic = 2.832 df = 3, p-value = 0.418			

	Most Frequent Study Partner			
	None (study alone)	Study w/ 1 friend	Study w/ 2 or more friends	Other response
Control	96	150	112	59
Solar lantern	37	60	62	27
	χ-squared test statistic = 2.961, df = 3, p-value = 0.398			

	Most Frequent Study Location				
	At home	At School (after school)	Friend's house	At School (before school)	Other response
Control	204	121	38	33	21
Solar lantern	95	47	22	10	12
	χ-squared test statistic = 3.354, df = 4, p-value = 0.5004				

Table 5: Responses to Light Use Questions and Pearson's Chi-square Tests of Independence

	Student's Most Used Light Overall (for studying and otherwise)					
	Flashlight	Solar Lantern	Mobile phone	Fire	Candle	Other response
Control	236	32	42	54	47	16
Solar lantern	118	26	12	10	17	4
	χ-squared test statistic = 16.905, df = 5, p-value = 0.005					

	All Types of Lights Used in Student's Household					
	Flashlight	Solar Lantern	Mobile phone	Fire	Candle	Other response
Control	309	70	164	124	131	57
Solar lantern	153	39	58	36	56	24
	χ-squared test statistic = 9.753, df = 5, p-value = 0.083					

Figure 2: Use of Different Types of Lights for Night Studies (endline survey, by treatment arm)

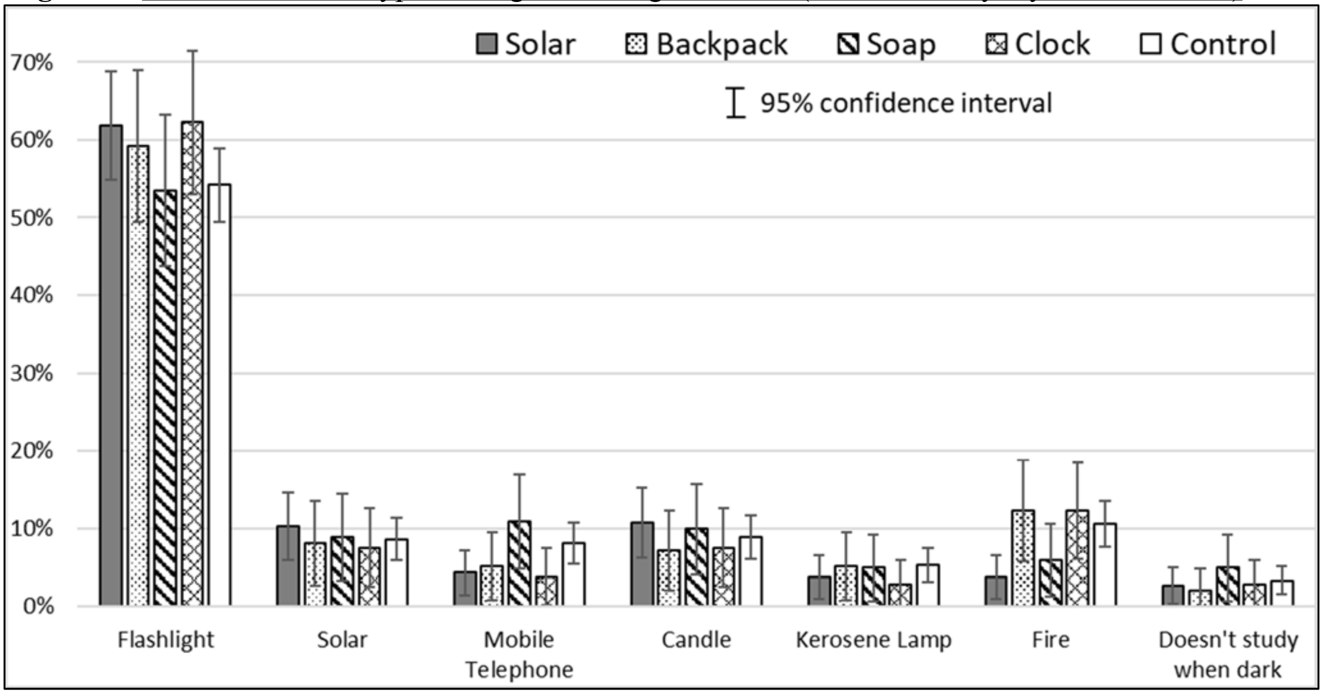


Figure 3: Solar Lantern Use in Solar Treatment and Control Groups (endline survey)

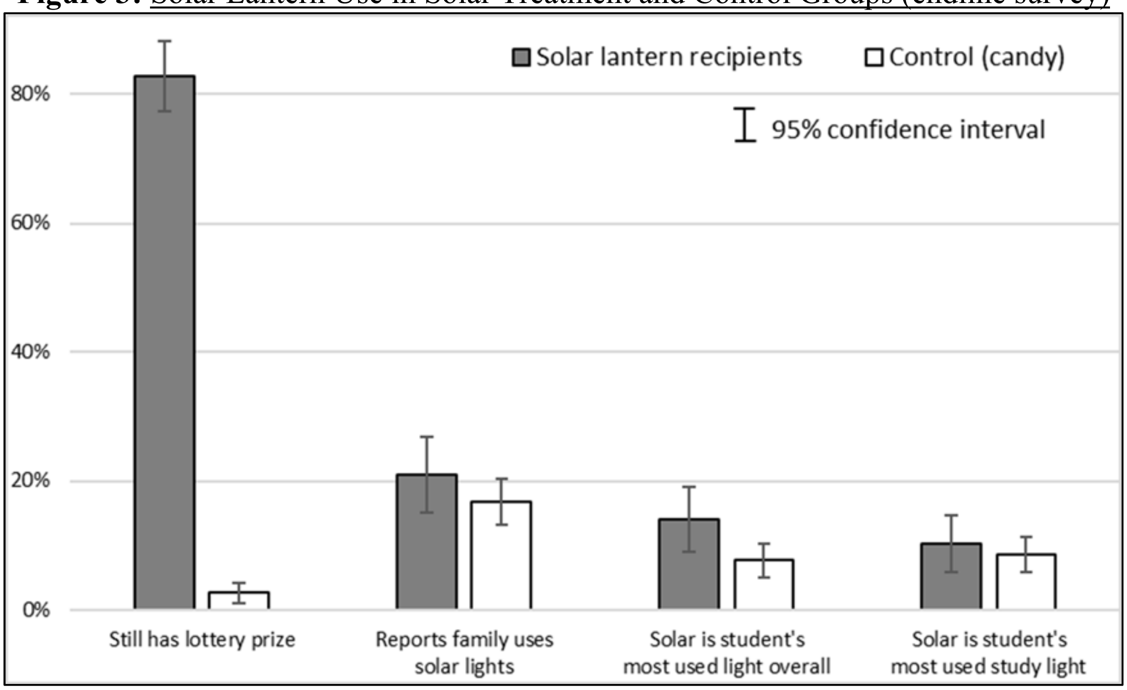
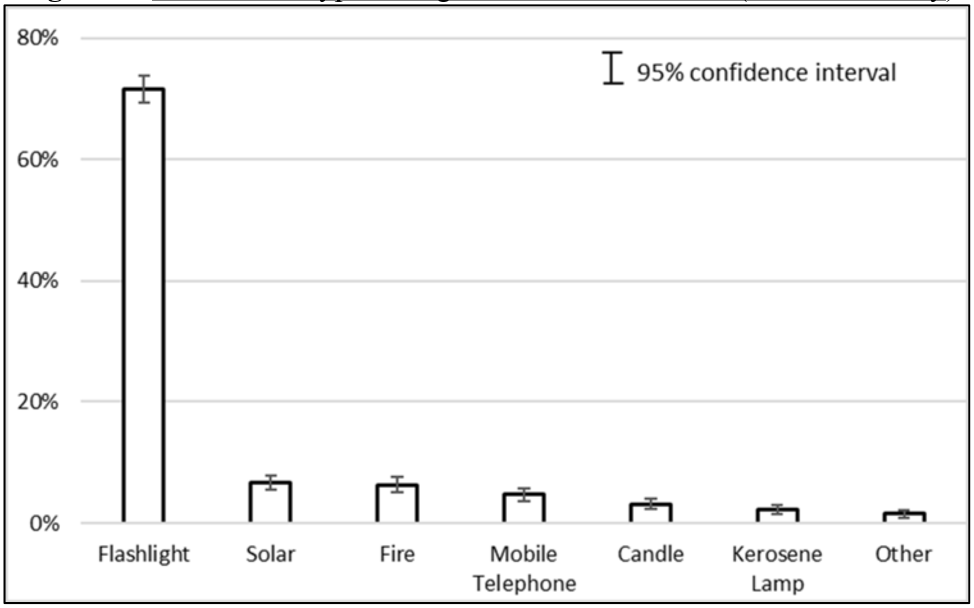


Figure 4: Most Used Type of Light in Student's House (baseline survey)



5.3 Comparison with Other Education-oriented RCTs and Cost-Effectiveness Analysis (CEA)

In order to place our results in context with other education-motivated interventions in the developing world, we follow the framework and methodology of Kremer et al. 2013 in their extensive CEA across 27 RCTs that aimed to improve test scores in developing countries. Figure 5 is a reproduction the central results of Kremer et al. 2013, whose underlying data is available from J-PAL 2019. We supplement their prior results with our own estimated impacts and cost-effectiveness of solar lights and backpacks, shown at the bottom of the figure in purple.

Looking at the left part of Figure 5, our results are consistent with the developing country education RCT literature. Specifically, the point estimates for the impacts of most educational interventions are increases of less than 0.2 standard deviations. Moreover, the majority of studies do not detect any impacts for their interventions on test scores, even with a generous 10% significance level (as shown graphically by the 90% confidence intervals). In addition, although our results are somewhat imprecise, our confidence intervals for the estimated impacts of solar lights are well within the magnitudes found in prior work on education in developing countries. We note, however, that our confidence intervals for the impacts of backpacks are much wider.

With respect to the CEA, shown in the right portion of Figure 5, we make the same assumptions and calculations that Kremer et al. 2013 do with the RCTs they considered. Their underlying data and calculations are available to download from J-PAL 2019, to which we added the costs and results from our RCT.[18] This enables us to estimate the additional standard deviation increase in test scores we would expect per $100 spent on distributing solar lights and backpacks to students in grade 7 in Zambia's Zimba district.[19] Although Kremer et al. 2013 would have excluded solar lights for grade 7 students from their CEA (because no impacts were detected at a 10% significance level), we opted to nevertheless include it in our own analysis for two reasons. First, our point estimate could be viewed as being promising enough and our estimate as imprecise enough, to argue in favor of undertaking the analysis to protect against the risk that our failure to detect impacts was due to our study being statistically underpowered (for example, due to too small of a sample size). Second, because solar lights are the focus of our study, the CEA helps us obtain a sense of the magnitude of impacts that would be needed (regardless of whether we actually detect them) in order for the impacts of solar lights to be considered economically meaningful relative to other policies that education-focused stakeholders may wish to pursue to boost test scores.

The CEA suggests that giving students solar lights is not a cost-effective way to improve test scores in developing countries. We estimate only an improvement of 0.1 standard deviations

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[18] This includes selecting the appropriate costs of the intervention to include in the calculations, as well as their process for converting everything to a set of "common units" through consistent adjustments for inflation, exchange rates, and calendar year of implementation. While any CEA is sensitive to such assumptions, we note that in our case, the sensitivity to exchange rates and inflation was lessened due to the short time-frame of our experiment and low inflation throughout the study and the years since in both Zambia and the United States.

[19] Following Kremer et al. 2013, we exclude the grade 9 results for the CEA because we could not detect an impact of the intervention for those students.

total, among the entire population that our sample is drawn from, for each $100 invested in distributing solar lanterns. This is far worse than all but 1 of the educational RCTs considered by Kremer et al. 2013. This calculation was made using the costs we actually incurred, but we believe it to be a lower bound on cost-effectiveness because our research staff could have distributed around 500 each of lights or backpacks (as opposed to the smaller numbers we actually gave away in our lotteries) without our incurring any additional fixed costs. If we take this into account by assuming our estimated impacts would hold if 500 lights or backpacks were to be given out, then the cost-effectiveness of solar lights and backpacks for grade 7 students would increase to 0.35 and 1.4 standard deviations per $100, respectively. With that assumption, the solar lights are still not a cost-effective intervention, although the backpacks start to seem more promising relative to other options.

It could also be argued that since solar lights and backpacks could both, in theory, just be bought on the open market in shops near Zimba, the purchase price for these items should be the only cost that should be considered in a CEA (as that price would already account for distribution costs of getting these items in the hands of Zimba district residents).[20] Under that more optimistic additional assumption, the backpacks become a potentially attractive option – their estimated 3.22 standard deviations gained per $100 compares quite favorably to most of the interventions in Kremer et al. 2013, although it would still lag far behind the five most cost-effective interventions they considered. On the other hand, the estimated cost-effectiveness for solar lights would still be only 0.75 standard deviations per $100 invested, which ranks well below all but one of the other RCTs in Figure 5. In fact, the average treatment effect of the solar

[20] This assumption is probably safer for the backpacks than for solar lights, both because the lights were not nearly as readily available in local markets as backpacks and because solar lights tend to break down and require after-purchase support.

lights would need to be a 0.37 standard deviations increase in test scores even under the most optimistic cost assumptions in order for their cost-effectiveness to rise to the median cost-effectiveness of the other education RCTs included in Figure 5. In that sense, the CEA suggests that solar light impacts of less than 0.3 standard deviations would not be economically meaningful, as they would not be cost-effective relative to other interventions available to policymakers who seek to improve educational outcomes in developing countries.

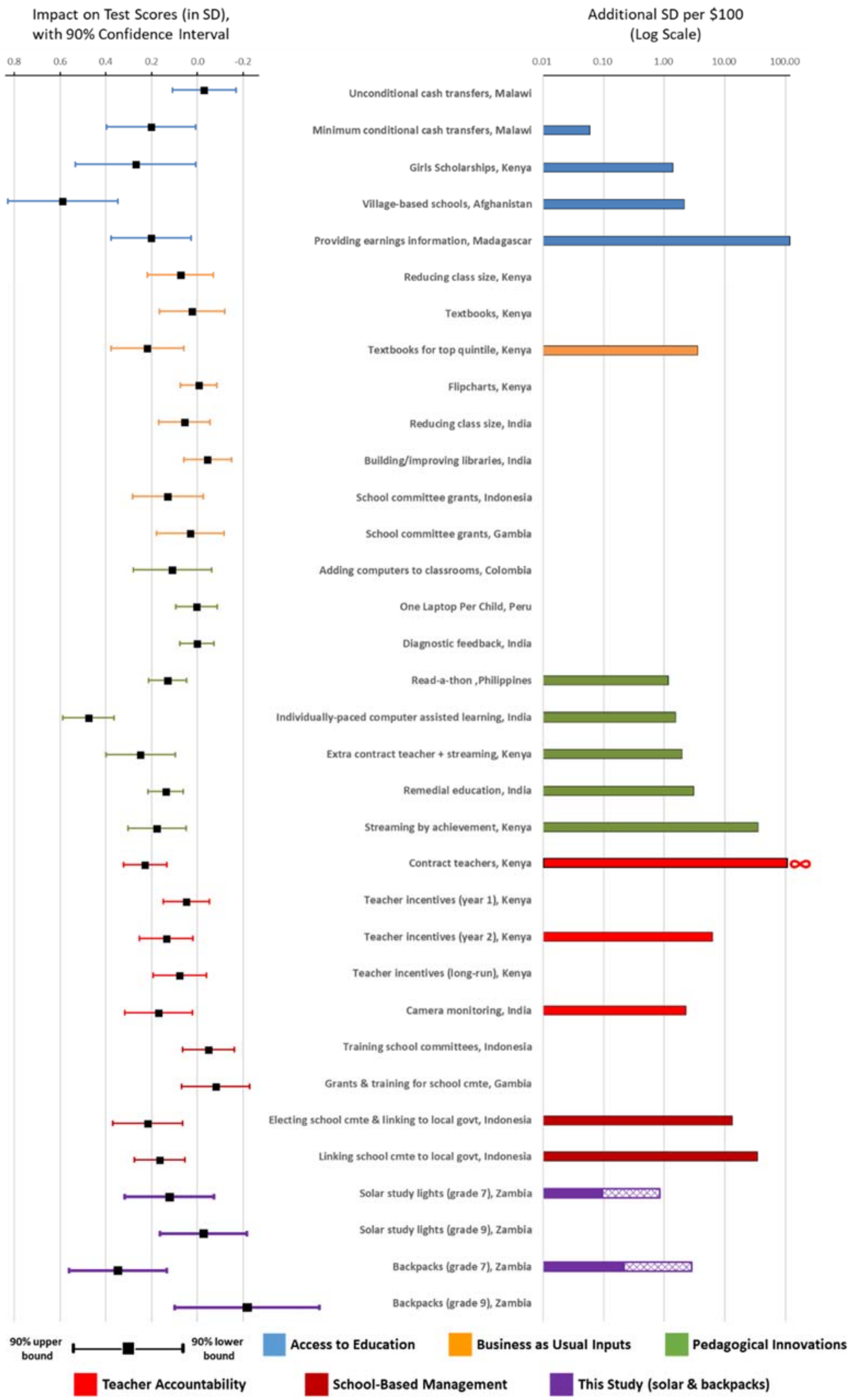
5.4 Precision and Statistical Power of Results

Although our estimates for the impacts of solar lights on examinations scores are somewhat imprecise, the results are still comparable to other education-focused RCTs in developing countries (see confidence intervals on left side of Figure 5). In an effort to assess the robustness of our estimates for the impacts of solar lights on examinations scores to alternative model specifications, we considered several additional specifications beyond those in our initial analysis plan. They are summarized in Appendix 4. We attempted adding several more pre-treatment covariates that we thought would be predictive of test scores, we pooled the scores from grades 7 and 9 to increase the sample size, and we also attempted pooling the "soap" treatment arm with our control group that received candy (as soap is theoretically not as direct of an educational input as the other prizes we gave away). Overall, our estimates for the impacts of solar lights on test scores under these alternative specifications were similar to the initial results presented in Table 3, and they are consistent with our conclusion that receipt of solar lights did not impact the test scores in our research sample.

In addition, we undertook an exploratory heterogeneity analysis to try and uncover any impacts of the lights if we were to cut the data by those students that might stand to benefit the most from solar lanterns, for example those who said that they did not primarily study in the dark at the time of the baseline survey. In addition, we looked to see whether we could identify effects based on which activity the children self-identified as their most important daily task (for example, going to school versus domestic work). We also estimated heterogeneous treatment effects by gender and age (in light of the large negative coefficients in our initial model for girls and older children). Regardless of which of these variables we interacted with the prize (treatment) variable, however, the F-statistics for joint hypothesis tests of the interacted variable coefficients were all far smaller than the critical value for a 0.05 test of the null hypothesis.

Finally, our failure to detect evidence of solar lights impacting examinations scores is most likely not due to a lack of statistical power to detect economically meaningful impacts, for example because of too small of a sample size. In Appendix 4, we also present the result of a power function calculation which suggests that if the solar lights did have economically meaningful impacts (around 0.3 standard deviations), then we would likely have detected them with at least a 0.8 probability. Therefore, our failure to detect impacts of those magnitudes, is evidence that such effects probably were not present.

Figure 5: Impacts on Test Scores from RCTs in Primary Schools in the Developing World



Source: Kremer et al. 2013 and J-PAL 2019, supplemented with authors' results

6. Discussion

In light of our results and those of the prior literature, which have also generally failed to detect educational impacts, we now undertake a closer look at some possible reasons why solar lantern adoption is not resulting in improved test scores. This discussion also allows us to place our study in context with the other research on solar lanterns, as well as the broader literature on educational innovations in developing countries. We first present several reasons why we believe solar lanterns may simply not appeal to children and households similar to those in Zimba District. Next, we argue that even if solar lanterns were to be widely used, a longer-lasting, brighter, and more comfortable lighting option might still not make much of a difference on test scores in places like Zimba, where there are many other more serious constraints on educational opportunities than insufficient lighting.

6.1 Low Rates of Solar Lanterns Use Severely Limit Potential Impacts

In order for solar lanterns to plausibly influence the outcomes of interest in this research, the lights would have needed to be used by the target end-users. As discussed in Section 5.2, expectations that solar lights might improve academic performance are predicated on solar lanterns being used to improve children's study environment. But it is also conceivable that there could be more complex mechanisms through which lights might impact academics beyond simply illuminating a study area.[21] Regardless of what the underlying mechanism might be, the

[21] For example, if the lights turned out to be better suited to enhancing work by children (paid or domestic) more than studying, then it would be more complicated to determine whether children working more efficiently is a net positive or net negative for their education. Relatedly, introducing LED lighting in a home for the first time might also shift sleeping habits, which could also impact academics in a more nuanced way. In our surveys, we collected data on children's daily activities beyond just schooling, their general use of lights beyond studying, and even their sleep times. We also tracked whether they kept or sold the lights we gave them (as we imagined that a sale of the light could also trigger more complex income effects). However, the observed lack of meaningful differences in mean outcomes between our treatment and control groups in the use of the solar lights for *anything* by any family members prevents us from exploring these more complex theoretical mechanisms in detail.

solar lanterns would need to be used for *something* by *someone* in order to trigger any impacts. Yet in our sample, solar lanterns were generally not used for studying, for other children's activities, or for any other use by a child's family (Figure 3). It is therefore not surprising that a treatment of disseminating lights, by itself and without subsequent widespread use, did not trigger economically meaningful impacts.

In this respect, our results are markedly different from the prior literature on solar lanterns (Kudo et al. 2017, Rom et al. 2017, Hassan and Lucchino 2016, Furukawa 2014). Although these studies also failed to uncover convincing evidence that solar lights improve test scores, they nevertheless reported or assumed extensive use of the lanterns.[22] We believe that our results are logically consistent and reflective of the realities of solar light distribution in areas like Zimba.[23] The differences in our study relative to the prior literature might be explained by two key features.

First, our research design decision to blind participants could be an important reason behind the low reported use rates. In the instances where we individually followed-up and asked children about their lights, they gave very different responses than to similar questions in the classroom survey, which the students had no reason to believe was related to the lights they had been gifted.[24] Other studies may have faced similar over-reporting of the use of solar lanterns.

[22] For example, Hassan and Lucchino (2016) suggest that solar lanterns trigger increased co-studying with fellow students on school grounds, as well as a shift in the time of day that children study. Meanwhile, Grimm et al. (2016) report extensive use of the lights for night studies, while Kudo et al. (2017) find that children used solar lights to study and that solar lantern use led to lower kerosene lamp use by their families.

[23] We do not observe use of the lights or impacts on educational outcomes, whereas the prior research contains potentially puzzling results that reports (or assumes) extensive solar lantern use but no further evidence of positive impacts on test scores or other objective measures.

[24] During brief in-person interviews where one of our enumerators (who was presented as a warranty support technician from a light vendor) sought out the solar lantern recipients, over 95% responded that they were regularly studying with the lights. However, when these same students were asked about solar lanterns during the endline survey–which was a broad "day in your life" type of questionnaire–only a small fraction indicated that they or someone else in their family used solar lights for anything. In addition, very few of the solar light recipients reported having problems using the lights during the individualized follow-ups, even though our "technician" enumerator alerted us to his own observations that some students seemed to be encountering technical troubles. Perhaps the

Even without a systematic bias to over report use, it is possible that participants in other studies were highly motivated to use the lights (which they otherwise may not have used) by virtue of their participation in a research project. For example, Hassan and Lucchino (2016) appear to have heavily promoted their goals to prove the positive benefits of solar lanterns, which may have triggered the use by hopeful children, parents and school officials.

An additional consideration, therefore, is the extent to which solar light use under different research designs reflects what would have happened if solar lights had been distributed by a commercial vendor in its regular course of business rather than through a research project. For our study in Zimba District, we attempted to mimic, as closely as possible, the practices of SolarAid, perhaps the best known market-based distributor of lanterns in the region (see details in Section 3). Moreover the in-person and written use instructions that we gave the children (Figure A1 in Appendix 3), as well as the proactive technical support that we attempted to provide, go beyond what most commercial enterprises offer and were designed to encourage the greatest possible light use, while still preserving our attempt to blind participants. Therefore, we do not believe that our research design discouraged the use of the solar lights and we instead believe it has high external validity to how lanterns may be used outside a research setting.

Second, we undertook our study in an environment where flashlights were the dominant household lighting source. This is different from the prior examinations of solar lanterns and education, as well as nearly all other studies of the off-grid solar space, for which kerosene was almost always the incumbent light. The high penetration rate of battery-powered flashlights in

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children did not feel comfortable being open about whether or not they used or experienced problems with something they had received for free.

Zimba initially surprised us, but we now suspect it may be common in much of rural Sub-Saharan Africa (see Bensch et al (2017), who report similar trends in seven more countries).[25]

Although the well-documented rise of the African solar lantern industry appears to validate a strong demand by rural populations to move away from kerosene lamps, it is far less clear how attractive solar lanterns are to prospective users that no longer use kerosene. The rise of the solar lantern market over the past decade has coincided with what is likely a much larger deployment of very affordable LED flashlights, albeit one that has been tracked and reported on far less. An important area of further research for impact-oriented stakeholders, therefore, is the extent to which even relatively low-quality LED flashlights might meet the lighting needs of prospective solar lantern adopters. The types of solar task lights that we studied may well face much greater "competition" from flashlights than they do from the diffuse lighting options that they are intended to displace (kerosene lights and diesel generators).[26] At the very least, the common assumption that the social benefits of LED lighting from cheap flashlights is inferior to that of solar lanterns should be critically examined (Bensch et al 2017).[27]

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[25] It is possible that the passage of just a few years between the data collection for prior published research on solar lanterns and our fieldwork in 2016 explains why, unlike prior studies, we encountered a population that had already largely stopped relying on traditional lighting. It may also be the case that rural populations in Zambia and other countries in Sub-Saharan Africa have historically used kerosene much less than Kenya and Uganda, which have been the setting for most of the prior published research on off-grid solar PV (see e.g. Stojanovski et al. 2017). In such settings, the key question is not whether a solar lantern is preferable to traditional options, as has been previously studied, but rather whether solar lanterns offer better lighting than the more modern bulbs found in flashlights or telephones.

[26] The most popular types of solar lanterns, including the ones used in our study, are known as task lights, which means they focus light on increasing the illuminance across a relatively small surface to help better accomplish a specific activity. This is in contrast with diffused lights that cast light in all directions to make their entire surroundings brighter, such as general household overhead lights. Therefore, the substitutability between flashlights—which are also task lights—and solar study lanterns may be especially pronounced. It is not clear whether more diffuse off-grid solar lighting (such as that offered by larger solar home systems) would hold more appeal relative to flashlights.

[27] Our experience during this and previous research has been that flashlights and phones are generally perceived by the solar industry's proponents as inferior options to solar lanterns (Mills et al. 2014; Kudo et al. 2017; Grimm et al. 2016). The flashlights sold in rural African areas, in particular, are often talked of as cheap, low quality, and/or inferior lighting sources that are unreliable, environmentally hazardous (because of the improper disposal of dry-cell batteries that power them), and that spoil the market for higher quality solar products (Mills et al. 2014).

6.2 Limited Opportunities for Better Study Lights to Improve Education

Prior research on solar lanterns has mostly assumed that insufficient lighting for studies (or other tasks) might be an important constraint on educational opportunities. We build on this work by more closely examining where improved lighting ranks relative to other schooling challenges faced by students in Zimba District and, by extension, similar regions across the developing world.

In general, not being able to study in the dark was not a major challenge for our sample, regardless of the type of study light used. Children in Zimba District were frequently assigned homework, and a significant portion, especially, girls, said they most often studied after sunset. However, nearly all respondents reported access to some type of lights for night-time studies. At the time of the baseline survey, only 10% said that not being able to study in the dark was a reason why they did not complete a homework assignment (Figure 6).[28] In addition, the types of lights that children reported studying with during either the baseline or endline surveys were not predictive of their national examination scores (see Appendix 5).

Financial poverty was the major constraint to our participants' educational opportunities. Children in our sample woke up early and had busy days, with the vast majority expected to help with domestic work, take care of relatives, or work to earn money. Only 53% identified going to school or studying as their most important responsibility.[29] Simply attending school regularly is a major challenge in Zimba. When asked to identify the reason for their most recent absence from

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Telephones, meanwhile, tend to have fairly dim and small LED lights and require a potentially inconvenient recharging outside the home, usually at a charging shop.

[28] Being too busy to do homework was cited by 31% of students – 16% for domestic work and 15% other work. (Other work includes employment where students earn money directly, as well as indirectly helping their parents to earn money.) There was a slight gender difference in the type of work children were engaged in that caused them to not complete school assignments, with girls doing more domestic chores and boys working outside the home,

[29] This question was asked in a survey students completed while in school so, if anything, we would expect bias toward over reporting the importance and prioritization of school attendance or studying.

school, the nearly all children selected options that related directly to financial barriers, such as an inability to pay school fees or not having enough supplies.[30] By contrast, not being able to study or finish homework (either because it was too dark or for any other reasons), was reported as a reason for missing school by only 8% of the children (Figure 7).

Overall, children in Zimba District appear to already be doing their best to study under difficult circumstances. In order to improve educational outcomes, they seem to need solutions that directly alleviate the financial challenges of schooling, which would be consistent with other research arguing that universal education initiatives succeed only when financial poverty is directly addressed (Lewin and Sabates 2012). There is little reason to believe that improved lighting can meaningfully address challenges with school fees, lack of supplies, or children being overwhelmed with too many responsibilities. Although there may be some association between increasing grid electrification and poverty reduction (see e.g. Lipscomb et al. 2013; Khandker et al. 2012; Khandker et al. 2013), more recent studies of energy access initiatives suggest that easing energy poverty does little to improve overall poverty (Lee et al. 2018; Burlig and Preonas 2018). Moreover, there is only limited evidence that solar lantern deployment in off-grid areas is linked with meaningful improvements in household finances.[31] As such, Zimba District could simply be a location where the financial barriers to schooling are so great that they render insufficient lighting a relatively unimportant educational input, which is in line with the conclusion of Kudo et al. (2017) in their examination of solar lanterns in rural Bangladesh.

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[30] The amount of fees in grade 9 in our sample was 6 to 13 times greater than the grade 7 fees.

[31] A handful of studies do examine this question closely and report some links between improved finances and solar lantern adoption (Kudo et al., 2017; Rom et al. 2017; [Aevarsdottir et al. 2017]). However, the size of the impacts they detect (typically 1-2% of reported expenditures) are likely far below the extent of financial poverty alleviation needed to address the barriers to education in Zimba district identified here, especially when one takes into account that respondents in these types of studies may well underestimate the expenditures they report.

The CEA presented in Section 5.3 further supports the notion that improved task lighting is not a promising way to improve education in Zimba District and elsewhere. We do not have the cost data from other studies of solar lanterns that we would need in order to also include their results in our CEA. However, providing children with solar lanterns is qualitatively most similar to the "business as usual inputs" category of Figure 5. These types of educational interventions in developing countries seem to have no impacts on test scores. Improved lighting is qualitatively different than the pedagogical interventions that seem to be much more effective in boosting scores. Moreover, other educational research has suggested that even promising interventions might yield little to no improvements if only one constraint is relaxed without meaningfully taking into account a broader spectrum of education inputs (see, generally, Glewwe et al. 2009). Therefore, there is little reason to expect solar lantern dissemination, by itself, to result in meaningful educational gains in locations similar to Zambia's Zimba District.

Figure 6: Reason for Not Completing a Homework Assignment (baseline survey)

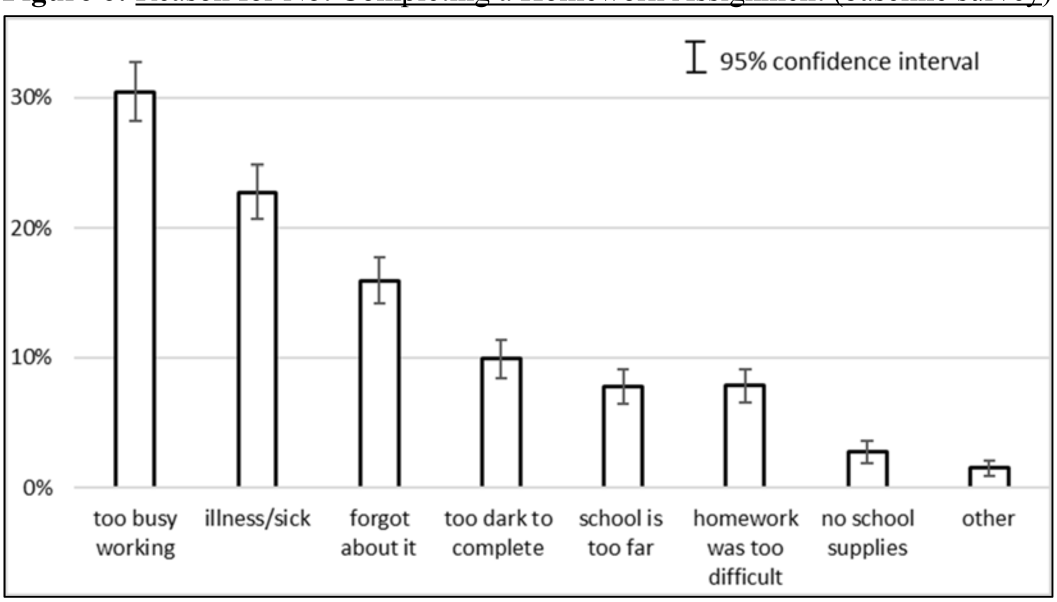
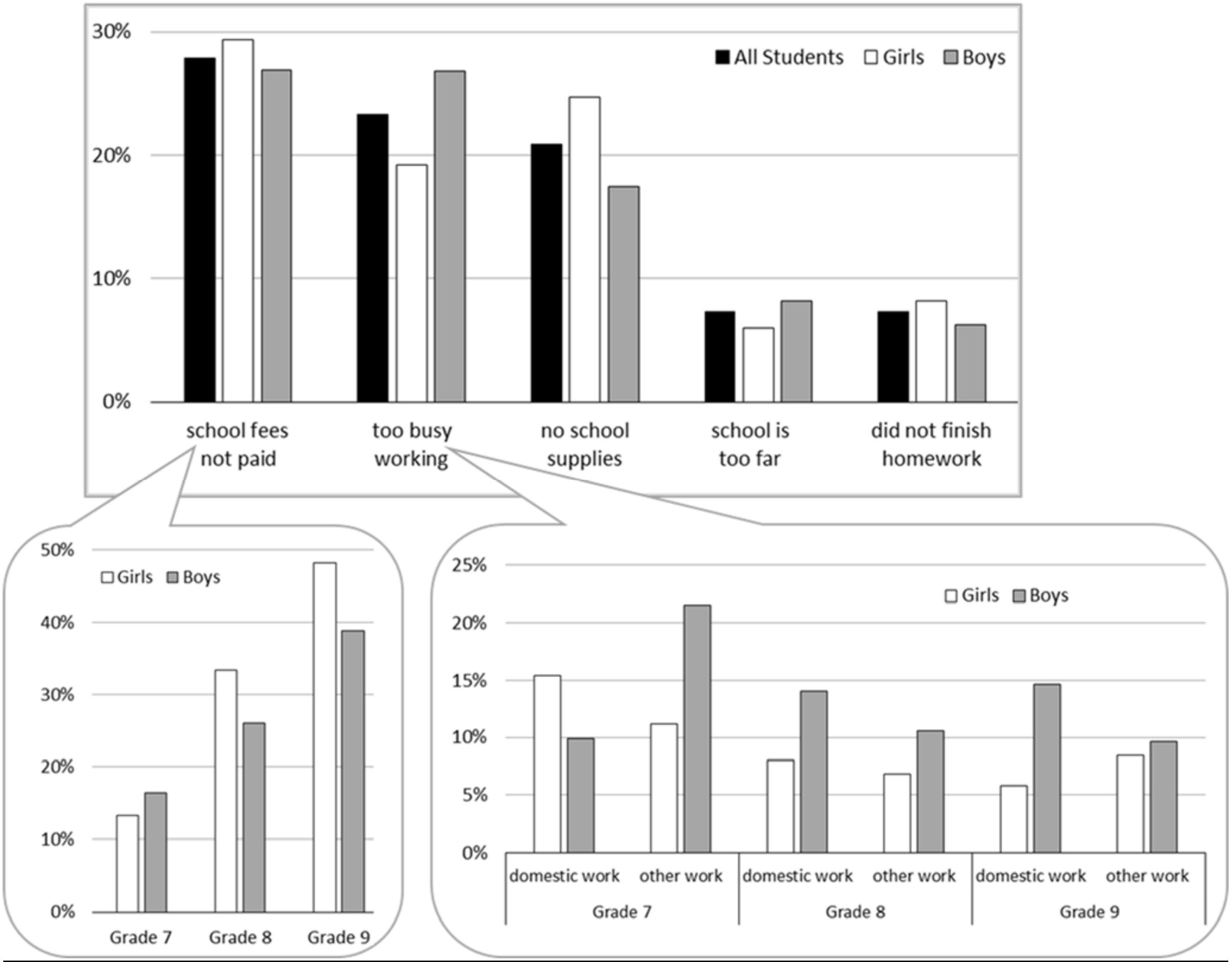


Figure 7: Reason for Not Attending School Other Than Illness (baseline survey)



6.3 Evidence that Backpacks Might Improve Test Scores for Some Students

Even though we did not initially intend to test whether backpack ownership boosts academic performance, the apparent positive impact from the gifts of backpacks to children in grade 7 is notable. Having new backpacks may have helped children take better care of their books and other scarce school supplies, the lack of which contributes to school absenteeism. It is also possible that owning a backpack instilled a sense of pride of attending school and feeling equipped to do so, which may be important in an environment where it is common to carry books in simple plastic bags. During scoping visits to households in the region, we observed that children and parents took great care to painstakingly wrap covers and take other measures to keep notebooks from wearing out. Zimba District is both a very dusty and rainy region (depending of the time of the year) so a backpack might be of great use in protecting school essentials, especially for the many children that walk several hours each day to and from school (children reported a median 70 minutes walking to school each way). However, backpacks as a promising educational interventions make sense only if they are used to carry books and other school supplies; so improved access to those educational basics would potentially do far more to improve education than simply providing backpacks. In this sense, backpacks are also just another "business as usual input" in the CEA framework presented in Figure 5, although a seemingly cost-effective one when targeted at students in grade 7.

We note, also, that the gift of a backpack did not appear to make a difference for students in grade 9. Our Zambian enumerators provided anecdotal reports that pre-existing backpack ownership rates were much higher in the grade 9 sample since children enrolled in that grade are generally better equipped and prepared for school. Many children from poorer families–especially girls–drop out of school between grades 7 and 9, something for which we find support in our survey data (the female to male ratio was over 60% lower in grade 9 than grade 7). So backpacks and the school supplies they are used to carry may not be in as short supply in grade 9 as in grade 7. Regardless of the mechanisms that may be at play with respect to the impact of gifting a child a backpack, our results for those in grade 7 are compelling enough to warrant inquiry in future research.[32]

[32] Interestingly, several recent social enterprise initiatives have recently tried to tie the prospective educational benefits of backpacks and solar lights by designing and distributing so-called "solar backpacks" (see, e.g. Forbes.com (2016))

Overall, we believe that solar lanterns did not appeal to our research sample because they could already easily (and affordably) access modern LED task lighting from flashlights. Moreover, the more fundamental obstacles to schooling faced by the population of primary school children we studied are so great that we now believe no amount of improved lighting—through solar lanterns, flashlights, or otherwise—could reasonably be expected to improve academic performance. Finally, even if solar lanterns were to somehow improve test scores, our CEA shows that they are not an effective policy tool relative to other available options. We therefore believe that the extensive survey data we collected provides new evidence to rethink the decade-long policy of supporting the deployment of solar lanterns in rural parts of Sub-Saharan Africa on educational grounds.

7. Conclusion

Despite the notable success of vendors selling millions of solar lanterns as study-promoting devices, there is still scant evidence that these lights actually improve educational outcomes. Our experiment in rural Zambia failed to detect impacts on standardized examination scores crucial to further educational attainment or on study habits that we had suspected might be key intermediary outcomes through which improved lighting might translate into better academic performance. Solar lanterns did not seem to have much appeal for the children we studied; they did not use the lights we gave them and insufficient study lighting was not a major problem they faced. In settings like Zambia's Zimba District, tackling energy poverty and introducing better ambient lighting might nevertheless be an important development goal in itself, but it would likely not improve schooling. For those looking to boost rural educational performance, there appear to be other more cost-effective opportunities. Our results suggest that perhaps providing backpacks or even simply just more books and school supplies could benefit some students.

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Assessing Opportunities for Solar Lanterns to Improve Educational Outcomes in Rural Off-Grid Regions: Challenges and Lessons from a Randomized Controlled Trial

Ognen Stojanovski (ognen@stanford.edu)
Program on Energy and Sustainable Development (PESD),
Stanford University

Mark Thurber (mthurber@stanford.edu)
PESD, Stanford University

Frank A. Wolak (wolak@stanford.edu)
PESD and Department of Economics, Stanford University

George Muwowo (muwowog@yahoo.co.uk)
Affiliated Researcher, PESD

Kat Harrison (kharrison@acumen.org)
Acumen

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SUPPLEMENTARY MATERIALS

Corresponding author: Ognen Stojanovski, PESD, Stanford, CA, ognen@stanford.edu

Appendix 1: Regression Results

Model 1:

$$exscore_{ij} = \alpha + ATE_{solar}(solar_{ij}) + ATE_{bpack}(bpack_{ij}) + ATE_{clock}(clock_{ij}) + ATE_{soap}(soap_{ij}) + \lambda_{school,j} + \epsilon_{ij}$$

Model 2:

$$exscore_{ij} = \alpha + ATE_{solar}(solar_{ij}) + ATE_{bpack}(bpack_{ij}) + ATE_{clock}(clock_{ij}) + ATE_{soap}(soap_{ij}) + \beta_{gender}gender_{ij} + \beta_{age}age_{ij} + \beta_{PPI}PPI_{ij} + \lambda_{school,j} + \epsilon_{ij}$$

Model 3:

$$exscore_{ij} = \alpha + ATE_{solar}(solar_{ij}) + ATE_{bpack}(bpack_{ij}) + ATE_{clock}(clock_{ij}) + ATE_{soap}(soap_{ij}) + \beta_{light}study\_light_{ij} + \beta_{time}study\_time_{ij} + \beta_{location}study\_location_{ij} + \beta_{partner}study\_partner_{ij} + \beta_{en\_speak}en\_speak_{ij} + \beta_{en\_write}en\_readwrite_{ij} + \beta_{gender}gender_{ij} + \beta_{age}age_{ij} + \beta_{PPI}PPI_{ij} + \lambda_{school,j} + \epsilon_{ij}$$

	(1) Standardized Exam Score (robust SE)		(2) Standardized Exam Score (robust SE)		(3) Standardized Exam Score (robust SE)	
	Grade 7	Grade 9	Grade 7	Grade 9	Grade 7	Grade 9
Treatment						
solar light	0.13	-0.04	0.12	-0.03	0.18	-0.04
	(0.13)	(0.12)	(0.12)	(0.12)	(0.12)	(0.12)
backpack	0.35	-0.22	0.35	-0.21	0.37	-0.12
	(0.14)	(0.20)	(0.13)	(0.19)	(0.14)	(0.19)
clock	-0.02	-0.11	-0.07	-0.05	0.07	-0.09
	(0.15)	(0.15)	(0.15)	(0.15)	(0.16)	(0.14)
soap	0.25	0.11	0.16	0.07	0.19	0.12
	(0.15)	(0.13)	(0.15)	(0.13)	(0.16)	(0.14)
Gender (1 = female)			-0.24	-0.20	-0.28	-0.06
			(0.09)	(0.09)	(0.10)	(0.09)
PPI (poverty index)			0.16	0.07	0.12	0.02
			(0.05)	(0.04)	(0.06)	(0.05)
Age			-0.13	-0.08	-0.11	-0.06
			(0.03)	(0.03)	(0.03)	(0.03)
English read/write difficulties					-0.42	-0.19
					(0.10)	(0.11)
English speaking difficulties					-0.05	-0.12
					(0.10)	(0.08)

study_light (reference = *flashlight*)		
solar	0.29	0.68
	(0.22)	(0.20)
mobile phone	0.10	0.16
	(0.16)	(0.13)
fire	0.54	0.17
	(0.25)	(0.25)
candle	-0.06	0.33
	(0.26)	(0.17)
kerosene lamp	-0.31	-0.27
	(0.18)	(0.56)
ZESCO	-0.01	0.29
	(0.25)	(0.20)
generator	-0.66	-0.22
	(0.22)	(0.36)
other	-0.55	NA
	(0.32)	NA
don't study when dark	0.58	0.56
	(0.69)	(0.23)
study_partner (reference = *none: I study alone*)		
1 friend	-0.15	-0.28
	(0.13)	(0.13)
2 or more friends	0.20	-0.03
	(0.17)	(0.14)
siblings	-0.07	-0.13
	(0.17)	(0.16)
parents/guardians	0.03	-0.66
	(0.20)	(0.23)
teachers	-0.26	-0.21
	(0.46)	(0.34)
doesn't study	-0.47	NA
	(0.38)	NA
study_time (reference = *after school before dark*)		
morning before school	-0.05	-0.27
	(0.17)	(0.18)
only during classes	0.22	-0.06
	(0.18)	(0.17)
evening after dark	0.13	-0.03
	(0.14)	(0.11)
very late at night	0.18	-0.09
	(0.12)	(0.12)
study_location (reference = *my house*)		
at school (after school)	0.12	0.20
	(0.11)	(0.10)
friend's house	0.03	0.08
	(0.19)	(0.16)
at school (before school)	-0.17	-0.24
	(0.19)	(0.27)
parents' workplace	0.16	-0.27

					(0.19)	(0.24)
in the fields					-0.14	0.28
					(0.38)	(0.28)
other					0.26	0.74
					(0.30)	(0.27)
doesn't study					-0.46	NA
					(0.50)	NA
school fixed effects (reference = 1)						
2	-1.00	-0.23	-1.02	-0.14	-1.07	0.08
	(0.23)	(0.13)	(0.23)	(0.15)	(0.25)	(0.18)
3	-0.84	-0.84	-0.50	-0.75	-0.50	-0.81
	(0.16)	(0.19)	(0.17)	(0.19)	(0.19)	(0.20)
4	-0.09	-0.48	-0.04	-0.42	-0.05	-0.18
	(0.26)	(0.23)	(0.24)	(0.24)	(0.24)	(0.26)
5	-0.07	-0.58	-0.09	-0.58	0.04	-0.33
	(0.18)	(0.15)	(0.18)	(0.15)	(0.20)	(0.15)
6	0.02	-0.45	0.02	-0.46	0.19	-0.32
	(0.23)	(0.20)	(0.22)	(0.22)	(0.24)	(0.23)
7	-1.35	-0.90	-1.20	-0.75	-1.16	-0.44
	(0.23)	(0.22)	(0.22)	(0.24)	(0.22)	(0.27)
8	-0.60	0.11	-0.31	0.21	-0.32	0.25
	(0.22)	(0.14)	(0.22)	(0.16)	(0.24)	(0.18)
9	-1.28	-0.12	-1.22	-0.07	-1.02	0.13
	(0.18)	(0.17)	(0.17)	(0.18)	(0.19)	(0.20)
10	-0.81	-0.24	-0.70	-0.23	-0.76	-0.05
	(0.18)	(0.14)	(0.18)	(0.15)	(0.20)	(0.17)
11	-0.62	-0.24	-0.49	-0.10	-0.68	-0.02
	(0.20)	(0.20)	(0.21)	(0.21)	(0.25)	(0.21)
12	-1.15	-0.89	-1.01	-0.91	-0.93	-0.69
	(0.26)	(0.20)	(0.26)	(0.19)	(0.26)	(0.22)
Observations*	403	318	403	316	377	301

Robust (heteroscedasticity-consistent) standard errors in parentheses

** The number of observations varies across specifications because some children left certain survey questions blank, including those used as covariates in some of the models.*

Appendix 2

Randomization Check – Balance of Sample

To check whether our randomization strategy worked well, we report the explanatory variables used in our analysis – which were collected during the baseline survey prior to the intervention lottery – broken down by treatment group (lottery prize) in Table A1.

Regressing each of these variables on the treatment variable (as assigned during our lotteries) reveals that most variables are reasonably well balanced, as summarized in Table A2.

Table A1: Baseline variables used in empirical models – by treatment group

Variable	**Sample Mean (Sample Standard Deviation)**				
	Solar Lantern **(N = 231)**	***Backpack*** **(N = 133)**	***Alarm Clock*** **(N =138)**	***Soap*** **(N = 131)**	***Candy (control)*** **(N = 578)**
gender – female (dummy)	0.52 (0.5)	0.47 (0.5)	0.53 (0.5)	0.37 (0.48)	0.48 (0.5)
age (years)	15.5 (2.11)	15.6 (2.11)	15.5 (2.1)	15.3 (1.64)	15.6 (1.84)
PPI wealth index (standardized score)	0.02 (0.96)	-0.06 (0.86)	0.06 (0.9)	0.12 (1.07)	0.05 (1.06)
speaking English difficult (dummy)	0.52 (0.5)	0.59 0.49	0.59 (0.49)	0.66 (0.48)	0.56 (0.5)
reading or writing English difficult (dummy)	0.28 (0.45)	0.36 (0.48)	0.36 (0.48)	0.29 (0.46)	0.26 (0.44)

Table A2: Empirical sample balance test – Regression Summary (Reference class is "Candy")

Dependent Variable (at Baseline)	**Explanatory Var. Regress. Coefficient (standard error)**				**Test-statistic (p-value)**	**N**
	Solar Lantern	***Backpack***	***Alarm Clock***	***Soap***		
+gender – female*	0.12 (0.11)	-0.03 (0.12)	0.13 (0.12)	-0.3 (0.13)	χ^2= 9.7, df = 4 (0.05)	1203
++age (years)	-0.06 (0.17)	0.02 (0.2)	-0.07 (0.19)	-0.21 (0.16)	F = 0.52 (0.72)	1211
++PPI wealth index (standardized score)	-0.06 (0.08)	-0.04 (0.08)	0.08 (0.09)	0.1 (0.1)	F = 0.62 (0.65)	1211
+speaking English difficult	-0.12 (0.11)	0.07 (0.12)	0.01 (0.12)	0.22 (0.13)	χ^2= 6.6, df = 4 (0.16)	1184
+reading or writing English difficult	0.14 (0.12)	0.24 (0.13)	0.24 (0.13)	0.08 (0.13)	χ^2= 8.6, df = 4 (0.07)	1193

+ probit model with dependent var regressed on treatment arm and school fixed effects

++ OLS model with dependent var regressed on treatment arm and school fixed effects

* sample imbalance along gender variable is driven almost entirely by the "soap" treatment arm, where the fraction of girls ended up being noticeably less than in the other four groups

Appendix 3

Research Design and Implementation Details

Table A3: Data Collection Details – Number of Students Surveyed

School Code[1]	Baseline Surveys Completed February 2016 (G = girls, B = boys)							Endline Surveys Completed October 2016 (G = girls, B = boys)						
		Grade 7		*Grade 8*		*Grade 9*			*Grade 7*		*Grade 8*		*Grade 9*	
	Total	G	B	G	B	G	B	**Total**	G	B	G	B	G	B
1	**129**	23	20	25	23	15	18	**103**	20	15	23	20	14	11
2	**120**	14	16	27	32	12	18	**115**	18	15	20	29	13	20
3	**182**	37	40	22	20	25	36	**158**	35	37	23	16	23	25
4	**120**	18	14	15	31	15	26	**98**	14	17	16	19	12	20
5	**110**	15	10	18	24	18	24	**85**	12	2	12	20	20	19
6	**86**	17	23	11	11	8	10	**83**	15	25	13	11	9	10
7	**97**	22	20	4	18	12	20	**88**	24	19	5	12	10	18
8	**181**	30	22	42	35	21	30	**129**	26	19	26	17	18	23
9	**187**	50	43	26	19	22	23	**180**	53	35	25	14	25	28
10	**175**	25	31	39	43	13	18	**174**	29	31	39	38	8	28
11	**99**	15	18	18	15	14	16	**88**	15	17	21	14	8	13
12	**102**	20	17	16	13	14	21	**108**	21	5	21	25	17	19
Total	**1588**	286	274	263	284	189	260	**1409**	282	237	244	235	177	234
(*% Sample*)	***100%***	***36%***		***35%***		***29%***		***100%***	***37%***		***34%***		***29%***	

Table A4: Randomized Controlled Trial Participation Details

School Code	Number of Lottery Participants (May 2016)	% Baseline Survey Participants that Participated in Lottery	Number of Students Matched as Having Completed Both Surveys*	% Baseline Participants Matched to an Endline Survey	% Endline Participants Matched to a Baseline Survey
1	96	74%	84	65%	82%
2	118	98%	84	70%	73%
3	134	74%	119	65%	75%
4	84	70%	90	75%	92%
5	78	71%	68	62%	80%
6	63	73%	66	77%	80%
7	58	60%	74	76%	84%
8	129	71%	110	61%	85%
9	181	97%	146	78%	81%
10	132	75%	133	76%	76%
11	67	68%	77	78%	88%
12	71	70%	71	70%	66%
Total	**1211**	**76%**	**1122**	**71%**	**80%**

* It is likely that more students completed both of our surveys but their two surveys were not confirmed as coming from the same person during the matching process, which was labor and time intensive.

[1] We randomly assigned each of the participating schools a research code number between 1 and 12 and do not identify them by name here in order to protect the privacy and anonymity of participating children and school employees. We also worked in a thirteenth school (which we assigned code 0) where we tested our data collection tools and methods, as well as treatment implementation strategies, but which was not included in our data analysis.

Table A5: RCT "Treatment Lottery" Details – Numbers of Prizes Awarded

School Code	Target Treatment Intensity[2]	Solar Lanterns (% lottery)*	Backpacks (% lottery)	Alarm Clocks (% lottery)	Soap (% lottery)	Control / Candy (% lottery)
1	30%	36 *(38%)*	6 *(6%)*	0 *(0%)*	6 *(6%)*	48 *(50%)*
2	0%	0 *(0%)*	16 *(14%)*	16 *(14%)*	16 *(14%)*	70 *(59%)*
3	20%	37 *(28%)*	18 *(13%)*	18 *(13%)*	0 *(0%)*	61 *(46%)*
4	0%	0 *(0%)*	15 *(18%)*	15 *(18%)*	16 *(19%)*	38 *(45%)*
5	10%	12 *(15%)*	11 *(14%)*	10 *(13%)*	12 *(15%)*	33 *(42%)*
6	10%	10 *(16%)*	8 *(13%)*	8 *(13%)*	8 *(13%)*	29 *(46%)*
7	30%	30 *(52%)*	0 *(0%)*	5 *(9%)*	5 *(9%)*	18 *(31%)*
8	10%	18 *(14%)*	18 *(14%)*	19 *(15%)*	17 *(13%)*	57 *(44%)*
9	0%	0 *(0%)*	25 *(14%)*	24 *(13%)*	24 *(13%)*	108 *(60%)*
10	20%	36 *(27%)*	0 *(0%)*	17 *(13%)*	17 *(13%)*	62 *(47%)*
11	20%	20 *(30%)*	10 *(15%)*	0 *(0%)*	10 *(15%)*	27 *(40%)*
12	30%	32 *(45%)*	6 *(8%)*	6 *(8%)*	0 *(0%)*	27 *(38%)*
Total		**231** ***(19%)***	**133** ***(11%)***	**138** ***(11%)***	**131** ***(11%)***	**578** ***(48%)***

* "% lottery" is the percent of lottery participants (students who completed the baseline survey *and* attended school on the day of the lottery) that won the relevant prize. It is larger than the target due to the absenteeism on the day of the lottery by children that had previously completed the baseline survey.

[2] The odds of winning a solar lantern varied across schools. We randomly assigned schools a percentage (30%, 20%, 10%, or 0%) that determined how many of the students that had completed a baseline survey would receive a solar light. We did this because there is limited insight on the relationship between solar light penetration rates and desirable social outcomes that might occur if students who do *not* own a light themselves might nevertheless benefit from increased ownership by others, for example because they study with a friend (see Hassan and Lucchino 2016). However, the low light use rates that we eventually observed in our research sample (see Section 5) ultimately prevented us from analyzing questions related to such "positive peer effects" or "positive learning spillovers".

Figure A1: Informational Card Given to Students that Received a Solar Lantern

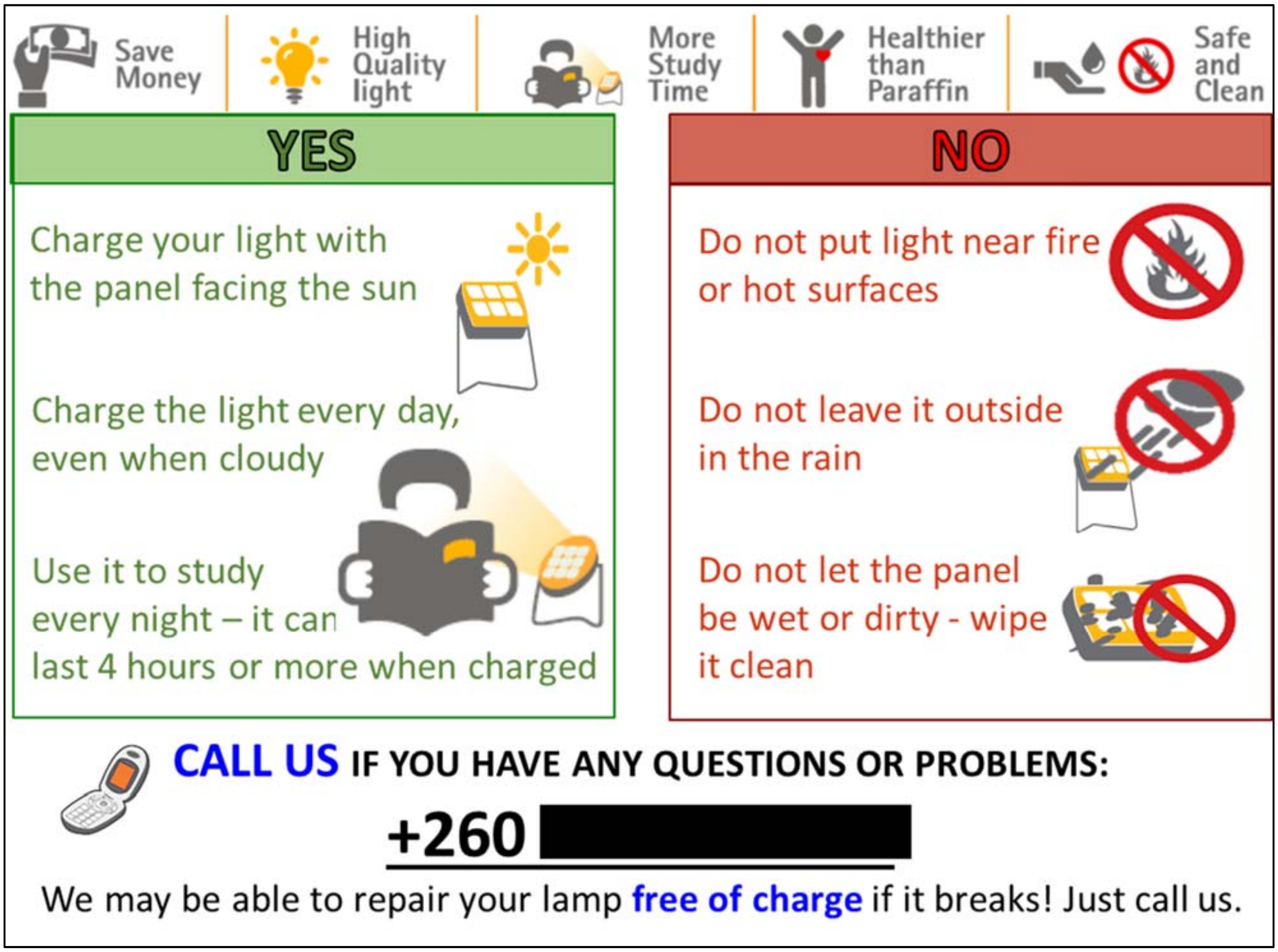


Figure A2: Photograph of common type of flashlight used by households in Zimba District

Appendix 4

Additional Discussion of Estimated Impacts and Statistical Power

In an effort to assess the robustness of our estimates for the impacts of solar lights on examinations scores to alternative model specifications, we considered several additional specifications that went beyond those in our initial analysis plan.

First, we added additional variables collected from the student surveys to our pre-analysis model specifications. We focused on how long it took children to walk to school and the extent to which they had missed school because their school fees were not paid, since the fees and long travel distances were repeatedly cited as leading reasons for school absenteeism by schooling officials throughout our research. However, our data did not reveal an association between these variables and examination scores, even though we were expecting a correlation between attendance rates and examination scores. Therefore, this additional specification did not meaningfully alter the precision of our results.

We also reran Models 1-3 after first pooling the "soap" treatment arm with our control group that received candy. Because soap is theoretically not as direct of an educational input as the other prizes we gave away, it could be argued that those children were also much like the control group. Once again, however, precision did not meaningfully increase, and the results were very similar to those of our prior specifications.

Finally, we also attempted pooling the standardized examination scores for children in grades 7 and 9. The results of this specification are trickier to interpret because the grade 7 and grade 9 Zambian examinations are very different from each other. However, pooling the grades nearly doubles the sample size of each specification and these results could still be interpreted, in a more abstract sense, as the impacts of the solar lights on some standardized exam (as opposed to the impacts of the specific test). Under this specification, the standard error for the estimated regression coefficient for the solar lights treatment is about 50% smaller than in the other specifications. However, we still fail to detect any impact of the lights on test scores. (And we no longer detect an impact of the backpacks on children in grade 7, as that effect is washed away by the inclusion of the grade 9 scores).

Our estimates for the impacts of solar lights on test scores under the alternative specifications described above are summarized in Table A6. They are quite similar to the results we obtained from our initial analysis plan (presented in Table 3), and they are consistent with our conclusion that receipt of solar lights did not impact the test scores in our research sample.

Table A6: Abbreviated Regression Results For Additional Model Specifications

	Standardized Exam Score (robust SE)				
Specification	Pooled scores for grades 7 & 9	Pooled soap with control group		Add commute time & school fees variables	
		Grade 7	Grade 9	Grade 7	Grade 9
Treatment					
solar light	0.08 (0.08)	0.1 (0.12)	-0.04 (0.11)	0.1 (0.12)	-0.01 (0.12)
backpack	0.11 (0.12)	0.32 (0.13)	-0.23 (0.19)	0.33 (0.13)	-0.21 (0.19)
clock	-0.04 (0.11)	-0.1 (0.15)	-0.07 (0.15)	-0.05 (0.15)	-0.08 (0.15)
soap	0.12 (0.11)	N/A	N/A	0.14 (0.15)	0.09 (0.13)
Observations	719	403	316	401	314

Robust (heteroscedasticity-consistent) standard errors in parentheses
These regressions also include gender, age, the PPI poverty index and school-level fixed effects as explanatory variables, the coefficient estimates of which are omitted for brevity. The pooled grades 7 and 9 scores model also includes grade-level fixed effects.

Our failure to detect evidence of solar lights impacting examinations scores is most likely not due to a lack of statistical power to detect economically meaningful impacts, for example because of too small of a sample size. We also conducted an *ex post* simulation of statistical power in order to help validate our *ex ante* power calculations[3] and support our claim that the failure to detect impacts of solar lights was not simply due to a lack of statistical power. To do so, we take Model 2 and the data we collected to perform the following:

First, we use each student's observed data for their outcome variable (standardized examination score), explanatory variables (treatment group, age, gender, poverty index, and school), and our estimates for the Model 2 coefficients to calculate the residuals ϵ_{ij} for each observation. We place those in a standalone residual vector for future sampling (the "residual vector").

Next, we generate a simulated set of outcomes (examination scores) for all students using the Model 2 equation. We fix all the coefficients for the explanatory variables except ATE_{solar} to be the initial estimates we calculated using Model 2. For ATE_{solar} we select and assign what the "real" impact of solar lights will be in the simulation. We then generate the simulated examination score for any given student by using the observed real-world data for that student's explanatory variables such as age and gender (which is multiplied by the relevant coefficients estimated through Model 2) plus a randomly-assigned residual that we obtain by sampling (with replacement) from our residual vector.

[3] Due to a lack of data from similar prior research, our *ex ante* power calculations were performed using the simple analytical formulas found in most statistical software for experimental sample size calculations. We assumed the control group would have a standard normal distribution, as we would be standardizing the national examination scores as our primary outcome of interest. We further assumed the treatment group's variance would also be equal to 1, as there was no prior literature or theory suggesting how receipt of a solar lantern would impact the variance of examination scores. We then varied the parameters for the probability of a type one error (between 0.05 and 0.1), the probability of a type two error (between 0.15 and 0.25) and the magnitude of the impacts we wanted to be able to detect (an increase in average scores of between 0.2 and 0.3 standard deviations). Assuming that about 25% of our sample would be treated with a solar lantern, these sample size calculations suggested that we would need a total sample of between 265 and 965. Our final samples for grades 7 and 9 fall within that large range, and reflect our attempt to assign as many students to the solar treatment as possible within the practical budget and design constraints for this experiment.

Once we have a complete set of simulated examination scores, we *rerun* Model 2 on the *simulated* data in order to determine whether we are able to detect the “real impact” of the solar lights (which we know to be present in the simulation because we chose and set ATE_{solar} to be a certain value). This “impact” is detected if the p-value associated with this estimate for ATE_{solar} in a two-sided test is below a pre-specified significance level. The simulation is then repeated 1,000 times. The estimated statistical power is the percentage of these 1,000 simulations in which we detect the specified impact (ATE_{solar}) of solar lights.

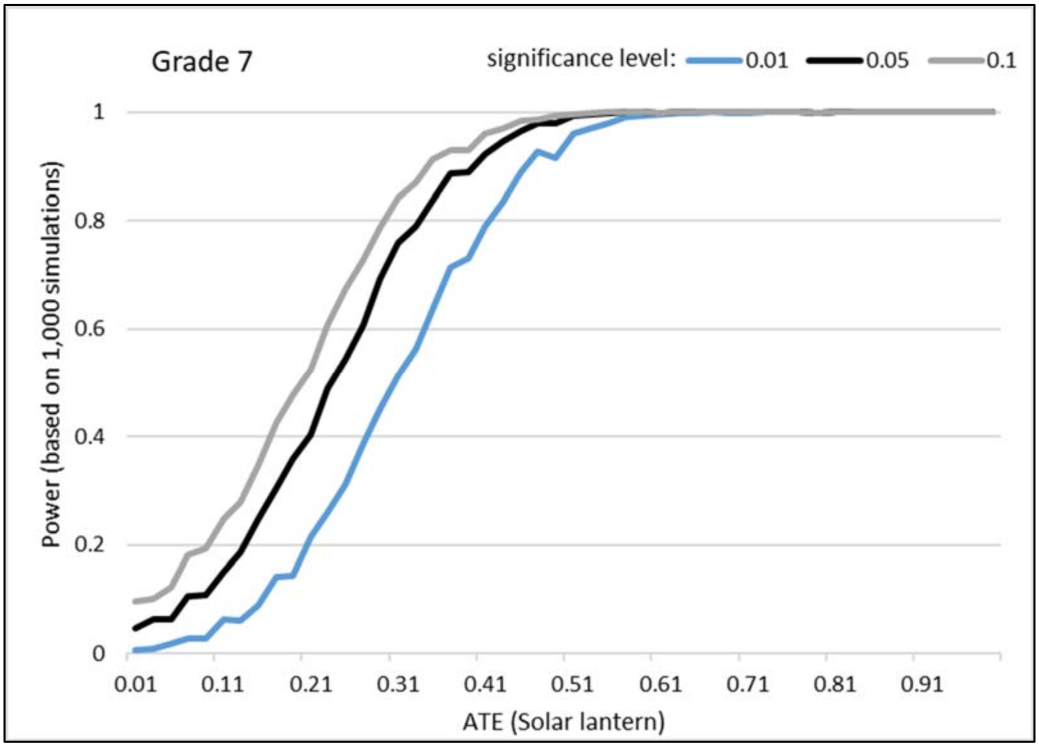
For each of grade 7 and grade 9, we ran 1,000 simulations for fifty different specifications of ATE_{solar}: from 0.01 to 0.99 sample standard deviations of our sample’s examination scores in increments of 0.02 standard deviations. Figure A3 shows a plot of these results. The y-axis in the figure is the percentage of the 1,000 simulations that any given “real” ATE_{solar} that we assigned (x-axis) was detected.[4] We plot the results for three significance levels: 10%, 5%, and 1%. We also plot analogous simulations for a range of potential impacts of backpacks (Figure A4). Here, we undertook the same steps described above except that we fix values of ATE_{bpack} rather than ATE_{solar}.

This estimated power function implies that if solar lanterns did somehow have an impact on examination scores in our sample (despite children failing to report use of the lights), the magnitude of any such impacts was likely less than 0.3 standard deviations. Our statistical power appears to have been sufficient to detect greater impacts, which would have more practical significance. This includes potential impacts that would have been as large as the effects that we

[4] For example, in the grade 7 plot, for an ATE_{solar} value of 0.01 standard deviations, only 43 of the 1,000 simulations resulted in an estimated impact of the lights with a p-value lower than 0.05. We thus plot a point at (x=0.01, y=0.043) for the 0.05 significance level line. Similarly, for an ATE_{solar} value of 0.50 standard deviations and a significance level of 0.10, 973 of the 1,000 simulations resulted in this impact being detected and so we plot (x=0.50, y=0.973) for the 0.10 significance level line

estimated backpacks to have had on the scores of 7th graders (estimated at around 0.3 standard deviations). In other words, if solar light had impacts that were as large as the effect that we estimate backpacks to have had in grade 7, then we would have detected those impacts with a greater than 0.8 probability in the case of both grades 7 and 9. Therefore, our failure to detect impacts of those magnitudes in either grade, combined with the analysis presented here, is evidence that such effects probably were not present to begin with.

Figure A3: Statistical Power Function Calculations – Solar Lanterns



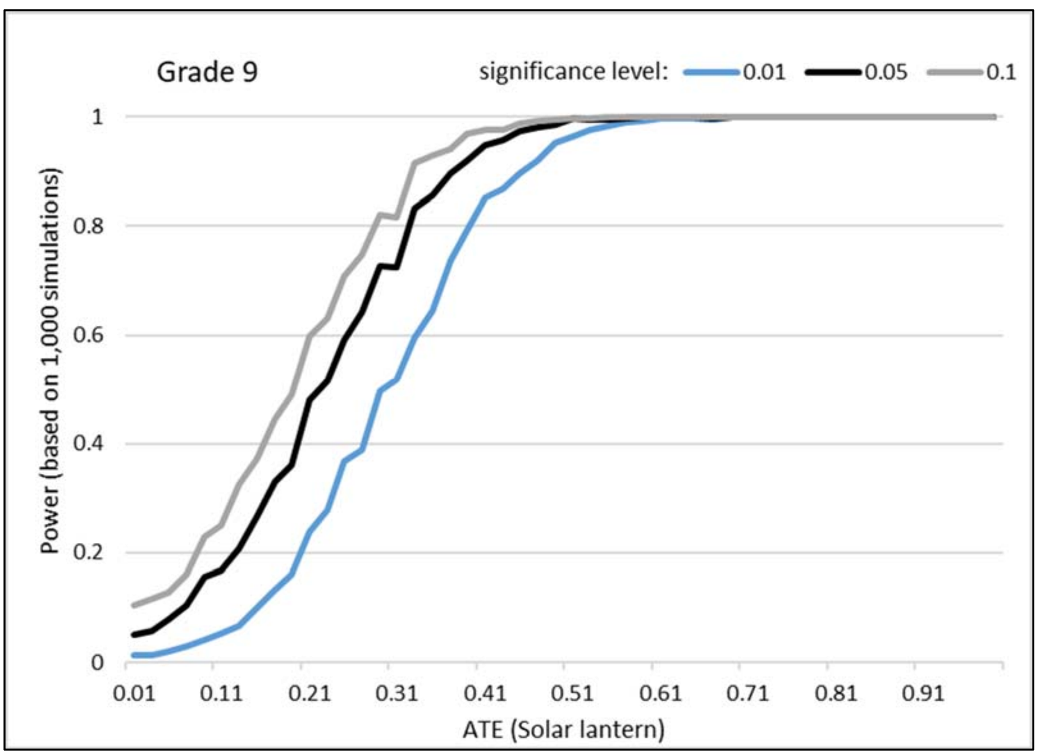
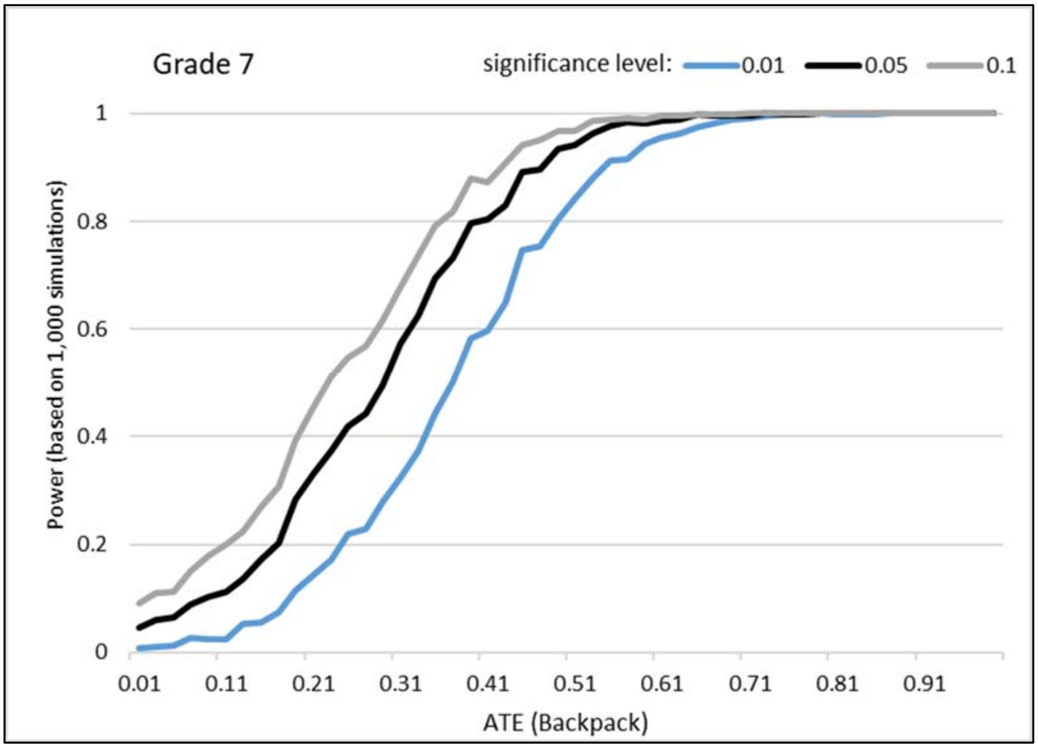
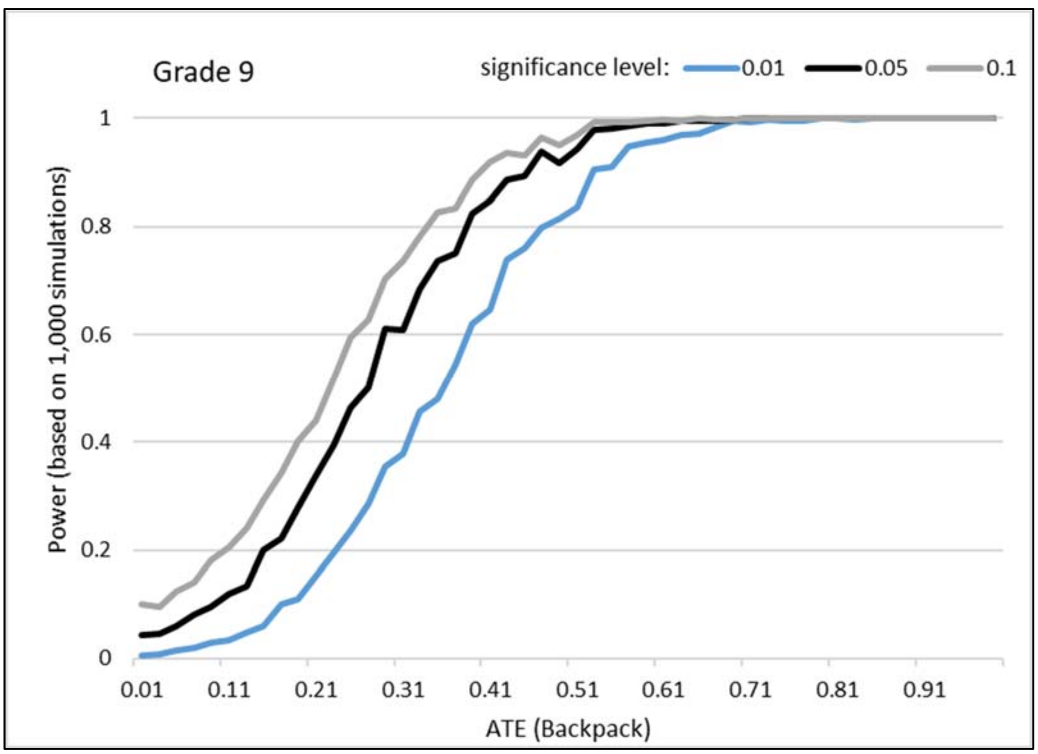


Figure A4: Statistical Power Function Calculations – Backpacks





Appendix 5

Additional Discussion of the Potential Associations between the Use of Solar Lanterns, Study Habits, and Test Scores

Although our intervention did not appear to impact the outcomes we tracked, we were nevertheless interested in *associations* that might exist between the kinds of lights that children self-report using to study with and test scores. Doing so allows us to take a first step toward better evaluating the theory that the mechanism by which solar lanterns might improve test scores would be through children using them to study (and perhaps also changing some of their other study habits). Model 4 identifies the extent to which test scores can be *predicted* by a student's self-reported *use* of solar lanterns (regardless of whether or not they received a lantern in our experiment). We also estimate whether the three other study patterns we tracked—most frequent time of day for studies, most frequent study partner, and most frequent study location—were predictive of test scores.[5]

Model 4:

$$\begin{aligned} exscore_{ij} = \alpha &+ \beta_{light} study\_light_{ij} + \beta_{time} study\_time_{ij} \\ &+ \beta_{location} study\_location_{ij} + \beta_{partner} study\_partner_{ij} \\ &+ \beta_{en\_speak} en\_speak_{ij} + \beta_{en\_write} en\_readwrite_{ij} + \beta_{gender} gender_{ij} \\ &+ \beta_{age} age_{ij} + \beta_{discuss\_secondary} discuss\_secondary_{ij} \\ &+ \beta_{fewer\_tasks} fewer\_tasks_{ij} + \beta_{paents\_help} parents\_help_{ij} \\ &+ \beta_{unpaid\_fees} unpaid\_fees_{ij} + \lambda_{school,j} + \epsilon_{ij} \end{aligned}$$

The variables in Model 4 are defined as in Models 1-3, except that the data used is from the endline survey rather than the baseline one. Using the endline survey data reveals associations between the examination scores and the state of the world, as reported by the children, very shortly before they took the tests. We also added four categorical variables that we

[5] The regression coefficients do not necessarily have a causal interpretation because we did not randomly assign the use of solar lights (just as we did not randomly assign a student's gender, whether they have difficulties speaking English, whether they studied with their siblings etc.).

theorized might also help explain scores: whether or not a student had discussed enrolling in secondary school with their parents (*discuss_secondary*$_{ij}$), whether a student's parents assign them fewer chores and work on days that they have homework (*fewer_tasks*$_{ij}$), whether parents help with or check over a student's homework (*parents_help*$_{ij}$), and whether a student had been sent home because school fees were not paid (*unpaid_fees*$_{ij}$).[6]

The results of the regression are shown in Table A7 below. We observe only limited associations between the examination scores and the kinds of lights that children report using to study, and even then only for the use of candles and phones in grade 7. Somewhat surprisingly, the other three study habits we tracked were also generally not very predictive of examination scores, even though we had expected that studying at certain locations, times of day, and with certain partners would help children learn more and do better (and especially because our data for this model was collected only days before the examinations).[7] This suggests that even if more children in our solar treatment group had used the lanterns we gave them, and even if solar lights had altered other study patterns, there may nevertheless not have been a further impact on academic performance.

Figure A5 shows the responses that all children who took both surveys gave, while A6 shows that the study habits of children in the solar and control groups were generally similar.

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[6] Unlike models 2 and 3, we did not fully specify model 4 prior to the start of our fieldwork. In particular, the four additional variables described above were added based on informal interviews with teachers and school officials in during our baseline data collection. However, we made the final specification prior to the data clean-up and analysis and the only other variable we considered including in the model was the reported distance of a child's home from their school, which was also cited by school officials as a leading cause of absenteeism. Moreover, unlike with models 1 through 3, we are not seeking to make any causal inference claims. Instead, we seek simply to identify whether the types of lights children report using to study, as well as the other variables in the model, reveal some predictive relationships between responses to our endline survey and examination scores. We therefore believe that our empirical approach is appropriate for this limited purpose.

[7] The few study habits that appear to be precisely estimated in Table A7 are mostly a result of only a handful of students selecting a given option. The only highly predictive variables for examination scores in Model 4, for both grades 7 and 9, were children's gender (with girls doing significantly worse), self-reported difficulty with reading and writing in English, and age (and, for seventh graders, whether or not they had discussed going to secondary school with their parents).

Table A7: Model 4 Regression Results

	(4)	
	Standardized Exam Score (robust SE)	
	Grade 7	Grade 9
study_light (reference = *flashlight*)		
solar	0.17	0.12
	(0.18)	(0.13)
mobile phone	-0.38	-0.10
	(0.18)	(0.15)
fire	-0.03	-0.04
	(0.17)	(0.11)
candle	0.34	-0.12
	(0.17)	(0.12)
kerosene lamp	-0.30	-0.21
	(0.28)	(0.16)
ZESCO	0.36	-0.27
	(0.35)	(0.35)
generator	NA	-1.28
	NA	(0.27)
don't study when dark	-0.10	-0.21
	(0.26)	(0.22)
study_partner (reference = *none: I study alone*)		
1 friend	-0.04	-0.21
	(0.12)	(0.12)
2 or more friends	-0.07	0.12
	(0.14)	(0.11)
siblings	-0.18	-0.18
	(0.16)	(0.19)
parents/guardians	-0.02	0.44
	(0.29)	(0.41)
teachers	-0.31	-0.31
	(0.27)	(0.16)
doesn't study	-1.14	NA
	(0.26)	NA
study_time (reference = *after school before dark*)		
morning before school	0.46	-0.18
	(0.19)	(0.21)
only during classes	-0.17	0.15
	(0.15)	(0.20)
evening after dark	0.16	0.16
	(0.12)	(0.09)
very late at night	0.31	0.06
	(0.12)	(0.10)
study_location (reference = *my house*)		
at school (after school)	-0.05	0.01
	(0.11)	(0.09)
friend's house	-0.20	-0.17

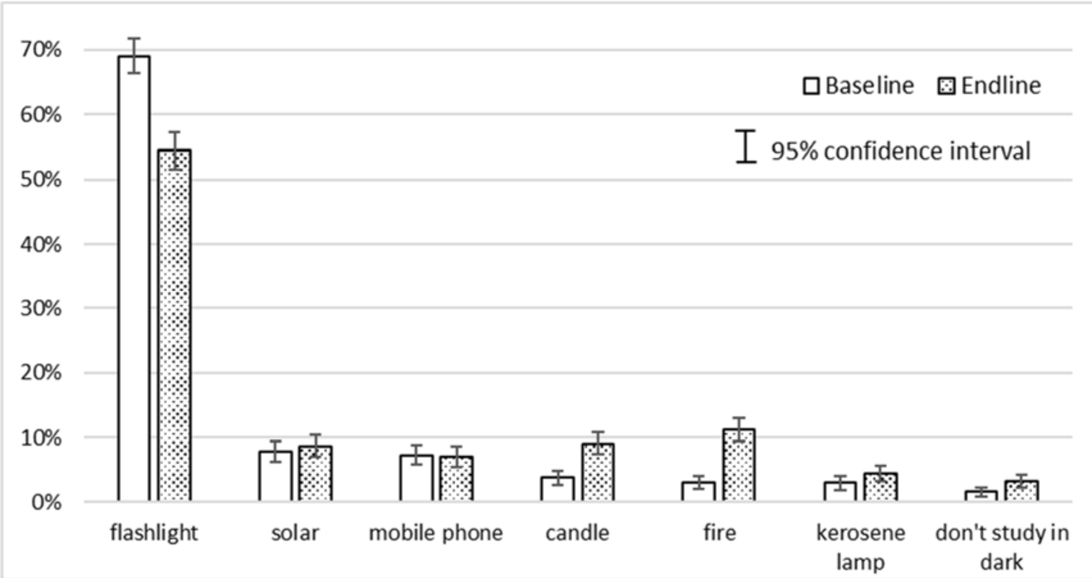
	(0.15)	(0.13)
at school (before school)	-0.09	0.10
	(0.14)	(0.22)
parents' workplace	-0.20	0.07
	(0.24)	(0.15)
in the fields	-0.22	-1.52
	(0.27)	(0.43)
other	-0.69	0.80
	(0.31)	(0.23)
doesn't study	1.05	0.38
	(0.31)	(0.73)
Gender (1 = female)	-0.29	-0.18
	(0.09)	(0.07)
Age	-0.10	-0.04
	(0.03)	(0.02)
English read/write difficulties	-0.31	-0.20
	(0.10)	(0.12)
English speaking difficulties	-0.21	-0.25
	(0.09)	(0.08)
discuss_secondary (reference = *“No”*)		
"Yes, a few times"	0.28	0.19
	(0.11)	(0.13)
"Yes, many times"	0.44	0.20
	(0.12)	(0.12)
fewer_tasks (reference = *“No”*)		
"Sometimes"	-0.07	-0.08
	(0.14)	(0.09)
"Yes"	-0.10	0.00
	(0.13)	(0.10)
parent_help_w_homework (reference = “*No*”)		
"Sometimes"	-0.03	0.07
	(0.13)	(0.11)
"Yes"	-0.11	-0.10
	(0.12)	(0.09)
unpaid_fees (reference = “*No*”)		
"Yes, a few times"	0.20	0.05
	(0.11)	(0.14)
"Yes, many times"	-0.06	0.12
	0.14	0.14
school fixed effects (reference = 1)		
2	-0.80	-0.40
	(0.27)	(0.16)
3	-0.52	-1.04
	(0.20)	(0.21)
4	-0.04	-0.42
	(0.24)	(0.17)
5	0.06	-0.76
	(0.21)	(0.15)
6	-0.04	-0.72

	(0.24)	(0.19)
7	-1.18	-0.79
	(0.23)	(0.21)
8	-0.11	-0.26
	(0.25)	(0.17)
9	-1.19	-0.20
	(0.22)	(0.16)
10	-0.84	-0.46
	(0.21)	(0.16)
11	-0.72	-0.08
	(0.26)	(0.16)
12	-0.86	-1.15
	(0.35)	(0.22)
Observations*	404	325

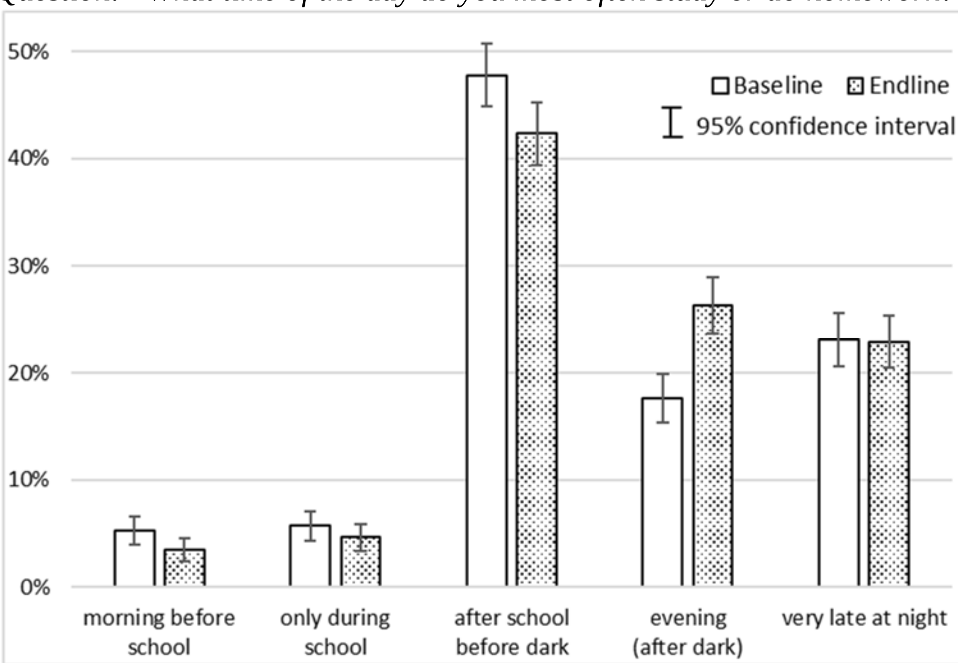
Robust (heteroscedasticity-consistent) standard errors in parentheses

Figure A5: Study Habit Summaries (all respondents who took both surveys, n = 1108)

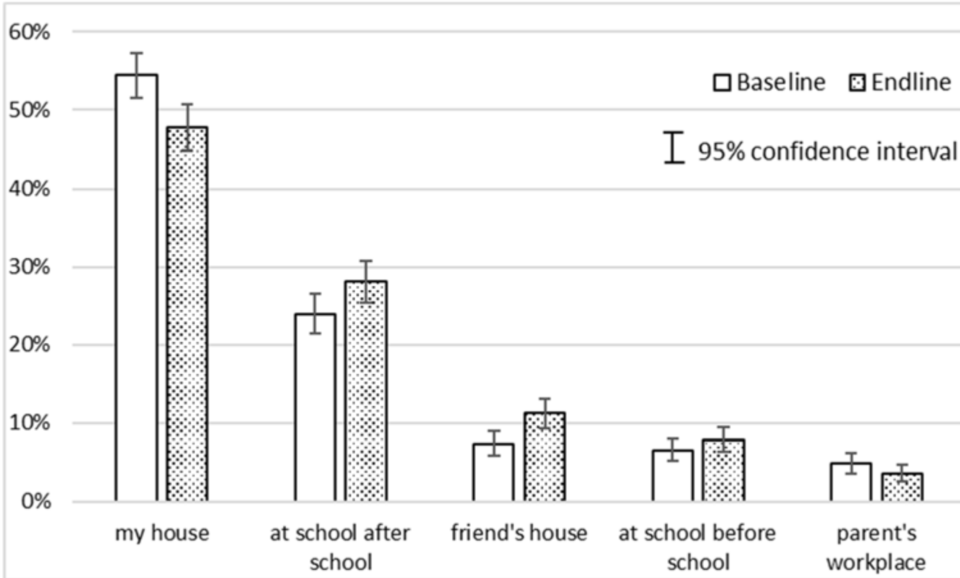
Question: "What kind of light do you use most if it is dark when you study or do homework?"



Question: "What time of the day do you most often study or do homework?"



Question: "Where is the one place where you study or do homework most often?"



Question: "Who do you most often study or do homework with?"

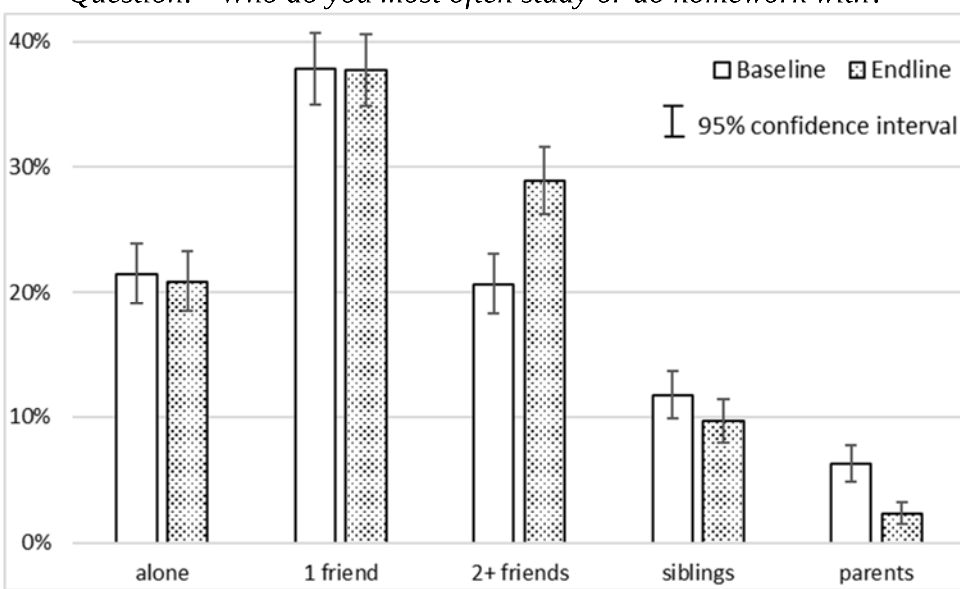
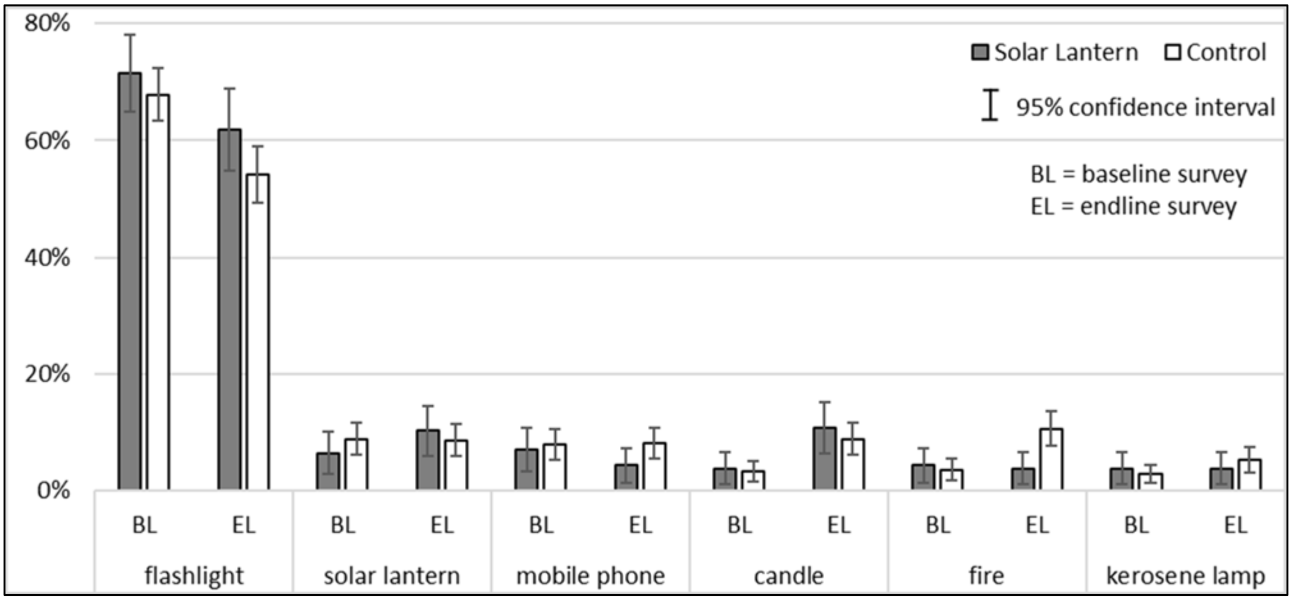
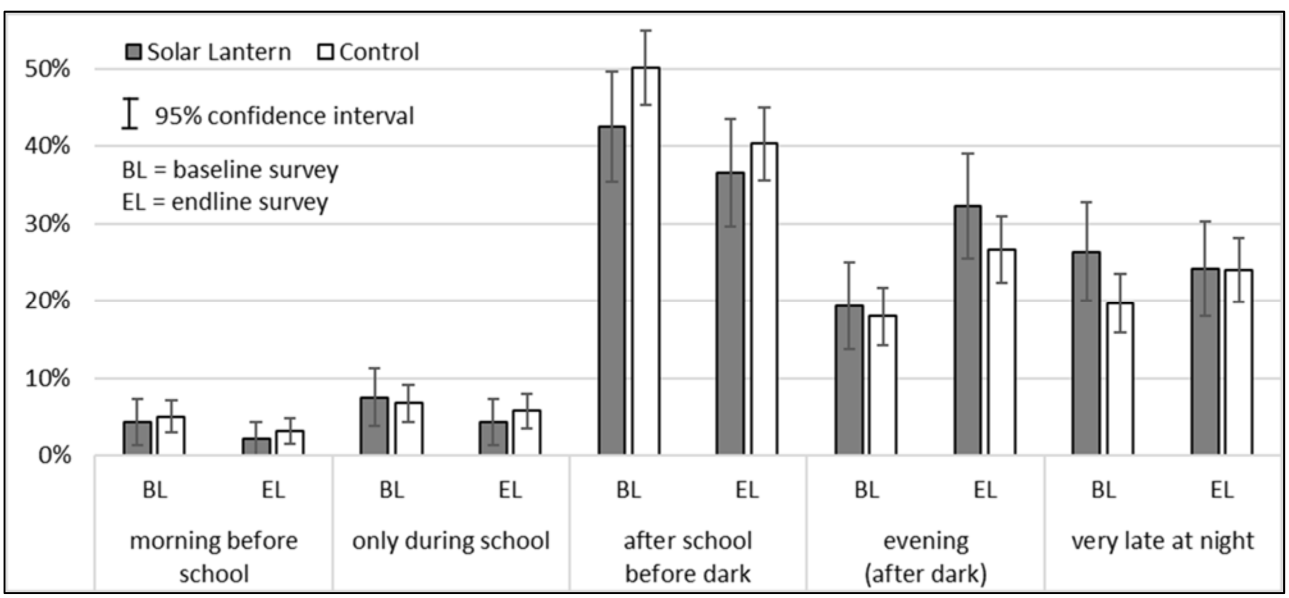


Figure A6: Study Habit Summaries – Solar Treatment (n = 186) vs. Control (n = 417) Group

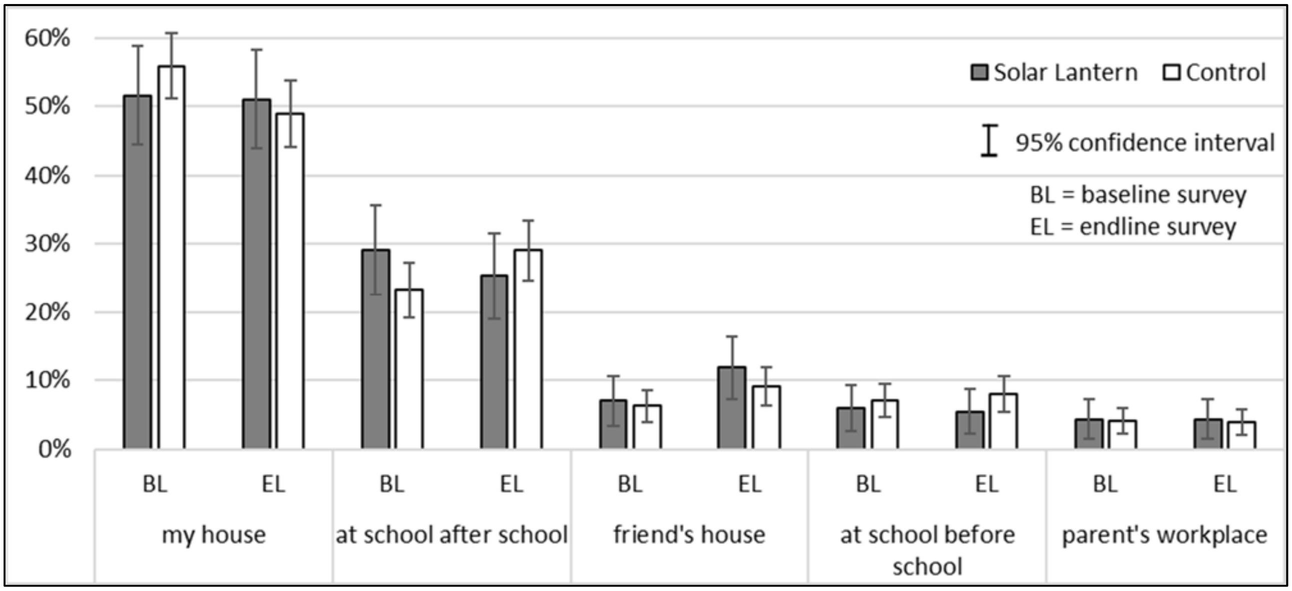
Question: "What kind of light do you use most if it is dark when you study or do homework?"



Question: "What time of the day do you most often study or do homework?"



Question: "Where is the one place where you study or do homework most often?"



Question: "Who do you most often study or do homework with?