Thermal Performance of Green Roofs:
A Parametric Study through Energy Modelling in Different Climates

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ABSTRACT: The widespread recognition and a growing literature of measured data suggest that green roofs can reduce building energy consumption. This paper investigates the potential of green roofs in reducing the building energy loads and focuses on how the different variables of a green roof assembly affect the thermal performance of a building in different climates. A green roof assembly is modelled in DesignBuilder and validated against field experiment data. Thereafter, the parametric study of the thermal performance of various green roof assemblies is carried out, altering one parameter of the green roof for each simulation run in order to understand its effect on building's energy loads. These parameters include different insulation thicknesses, leaf area indices (LAI) and soil depth. The performance metrics of these assemblies are compared with each other and to a cool roof base case to determine the energy load reductions, if any. The simulation results are then organized and finally presented as a decision support tool that would facilitate the adoption of green roof technologies and make it possible to account for green roof benefits in energy codes and related energy efficiency standards and rating systems such as LEED.
Keywords: energy modelling, green roof, simulation, thermal performance, parametric study

INTRODUCTION

Green roofs have become important to green building practices, as a response to mitigating the negative impacts of Urban Heat Island. These roofs, also known as eco-roofs, living roofs or vegetated roofs, are partially or completely covered with vegetation and a growing medium, planted over a water-proofing membrane. They may also include additional layers such as root barrier and drainage and irrigation systems. Green roofs differ from the conventional roofs because they act as a heat sink- an active energy device, literally collecting, processing, and releasing energy according to its immediate need. The evapotranspiration of plants cools the roof by using the heat to evaporate the water from the growing medium and plant surface. In addition, the shading provided by the plants reduces the amount of sunlight hitting the roof. This helps to reduce the indoor and outdoor temperatures in the building and urban area depending on the type of vegetation, depth and type of growing medium and local climate. This in turn helps to reduce the cooling load of a building, resulting in reduced air cooling requirements and therefore reduced energy consumption and associated output of atmospheric carbon.

This paper investigates the quantitative benefits of building energy load reductions over a cool roof base case, caused by different parameters of a green roof assembly. The different thermal performance metrics investigated in this study include the energy use intensity (EUI), annual and peak heating and cooling loads and heat flux through the roof.

ENERGY MODELING OF GREEN ROOFS

A quantitative and physically-based building energy simulation tool that represents the effects of green roof constructions facilitates the process of assessing green roof benefits, thereby enabling one to make an informed decision regarding the green roof assembly selection. A physically based model of the energy balance of a vegetated rooftop has been developed by Dr. David J. Sailor, a Professor of Mechanical and Materials Engineering and Director, Green Building Research Laboratory at Portland State University. His model has been integrated into the EnergyPlus building energy simulation program. This green roof module allows the energy modeller to explore green roof design options including growing media thermal properties and depth, and vegetation characteristics such as plant type, height and leaf area index. The model has been tested successfully using observations from a monitored green roof in Florida.

For the purpose of this study, DesignBuilder- a 3D graphical design modelling and energy use simulation program- is used. The simulation engine EnergyPlus, which is well integrated within the program, runs all the necessary calculations related to the building energy model (BEM) and reports the results within the Design Builder interface.

VALIDATION STUDY

A validation study is first carried out to ascertain the accuracy of the modelled green roof assembly. Dr.

Steven Sandifer's field experiment is chosen for this purpose. A green roof module was constructed by him and the inner surface temperature of the assembly was recorded along with other weather data. His setup is replicated in DesignBuilder by the author and simulations are run for a week in August. The measured data is then compared with the simulated data to observe the correlation and trend between the two data sets. It is seen that the simulated data is consistently higher than measured data by around 3.9°F and the trend of the data scatter is similar in slope to the ideal case (where measured data= simulated data) but suffers from a lateral shift which may be caused due to the exclusion of weather data like solar radiation and relative humidity in the calculation of the surface temperature. However, if the simulated data set is multiplied by a factor (0.96= inverse of the slope of trend line), a substantial agreement between the two data sets is noted (Fig. 1).

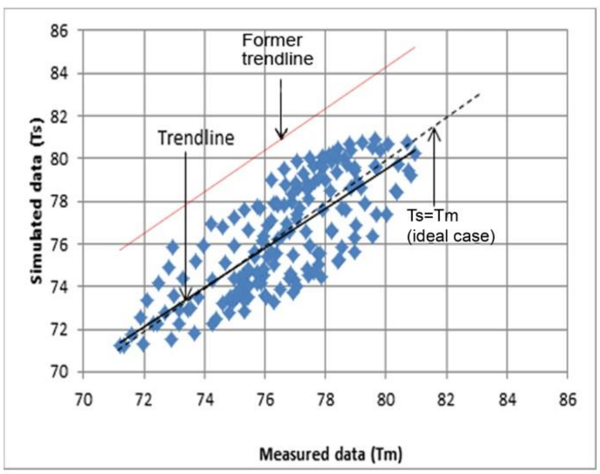


Figure 1: Correlation between measured and simulated data, after adjustment

Either way, the absolute percentage difference between the data sets is within 10% which indicates reasonable accuracy of the model. Upon validation, this model is then used for further parametric testing on a prototypical building.

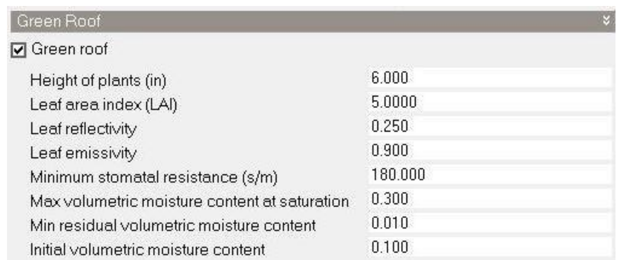
BUILDING ENERGY MODEL (BEM)

Building prototype:

The parametric study is carried out on a small sized (10,000 sq. ft roof footprint) office building of a single story. The prototype is constructed as a code compliant building, referencing to Commercial Buildings Energy Consumption Survey (2003 CBECS), American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE Standard 90.1-2004) and ASHRAE Ventilation Standard 62.1-2004 (ANSI/ASHRAE 2004) for building envelope information, operating schedule recommendations and ventilation requirements. References to the U.S. Department of Energy (DOE) Commercial Reference Building Models, developed by Pacific Northwest National Laboratory (PNNL) have also been made, while developing the model. The base case model is developed with a cool roof, which is the code requirement for any new construction in California currently. The green roof model differs from the base case only in the construction of the roof assembly.

Green Roof Model Description:

In the Design Builder modelling environment, the green roof is present as 'Ecoroof' material that forms the outer layer of the roof assembly (metal deck). Certain parameters pertaining to the vegetation layer or growing medium are present that help to define the green roof type, like as shown in Fig. 2.



Green Roof	
☑ Green roof	
Height of plants (in)	6.000
Leaf area index (LAI)	5.0000
Leaf reflectivity	0.250
Leaf emissivity	0.900
Minimum stomatal resistance (s/m)	180.000
Max volumetric moisture content at saturation	0.300
Min residual volumetric moisture content	0.010
Initial volumetric moisture content	0.100

Figure 2: Green roof parameters related to vegetation (Ecoroof layer)

Apart from the vegetation layer, the green roof comprises a growing medium (soil) of certain depth, a root barrier membrane, a drainage layer, insulation (may or may not be present) and a waterproofing membrane. The structural roof is a metal deck, same as in the base case of a cool roof. A cross-section through the entire green roof assembly as modelled is illustrated in Fig. 3.

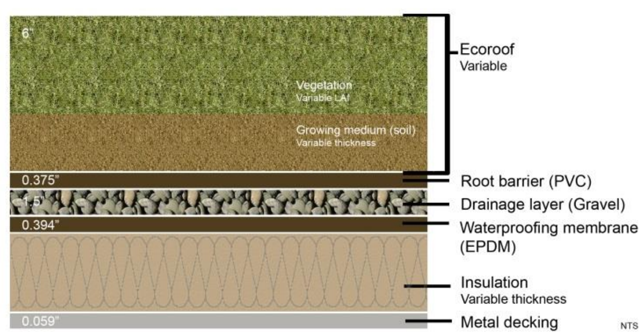


Figure 3: Different layers of the green roof assembly as modelled in DesignBuilder

Each layer of the green roof deals with heat flow differently. The depth of the topsoil and type of plant chosen would vary the insulation values owing to different U-values. Both the plants and substrates increase the R-value resulting in energy cost savings. Also, the moisture content in the soil affects the heat flow through it. The modelled roof is irrigated. The green roof irrigation is set to a smart schedule which means that the roof is irrigated according to the maximum irrigation rate (feet per hour) input, and overrides the irrigation schedule to be turned off when the soil is 30% or more saturated with water, so as to avoid over watering of the roof.

Limitations of Green Roof Model:

It is important to note here that Sailor's model has only been tested with the ConductionTransferFunction (CTF) solution algorithm, and any other solution algorithm choice would give an error during the simulation. Also, there are limitations on the data input, for this algorithm to work. The input data ranges have been clearly defined in the EnergyPlus documentation, The Encyclopaedic Reference to EnergyPlus Input and Output.

TEST PARAMETERS

The different green roof assembly types are tested for the following three different climate types-

- Hot dry- Phoenix, AZ *(cooling dominated climate)*
- Warm Coastal- Los Angeles, CA *(heating+cooling)*
- Cool humid- Chicago, IL *(heating dominated climate)*

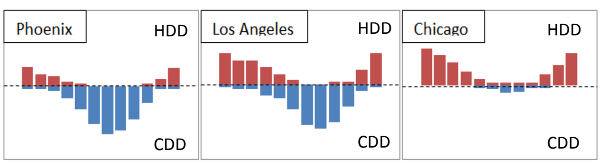


Figure 4: Heating and cooling degree day (HDD/CDD) chart, highlighting the spectrum of climate types covered in this study

The green roof parameters that are tested are illustrated in Fig 5. Each of these parameters has their subset variables. A total of 24 different green roof assembly types are generated as a result of the combination of these parameters. The nomenclature used to refer to each of these variables is indicated in parentheses under the variable type.

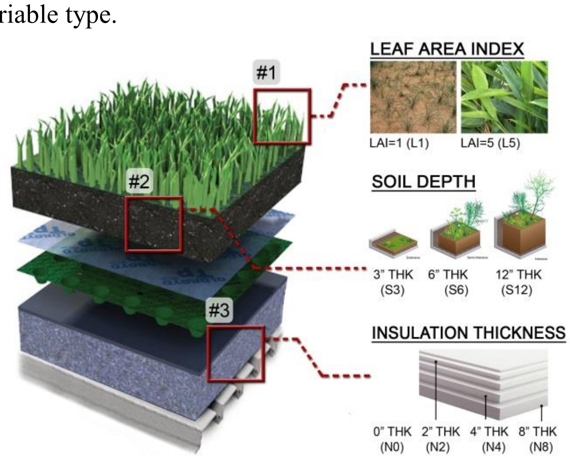


Figure 5: Variable test parameters of the green roof assembly

SIMULATION DATA ANALYSIS

The annual energy simulations are carried out for the baseline cool roof model and green roof model and the energy use intensity (EUI) of the building is observed as a performance metric, in addition to a few others like peak heating and cooling loads, heat balance through the roof etc. With each subsequent simulation one variable of each parameter of the green roof assembly is altered and the effect on the above mentioned metrics is noted and reported as percentage reduction over base case.

Performance metric- EUI:

The bar charts in Fig 5. illustrate the best and the worst performing assembly with respect to reduction in EUI and compare it to the other assemblies, for all three climate types. It is observed that Phoenix has the highest reduction in EUI (up to 8%) while Chicago has the lowest EUI reduction (2.4%) caused by green roofs. All assemblies for Phoenix and Los Angeles perform better than base case, but there are 10 assembly types that perform worse than base case for Chicago. The negative impact of these assemblies over base case has been highlighted in the dotted box.

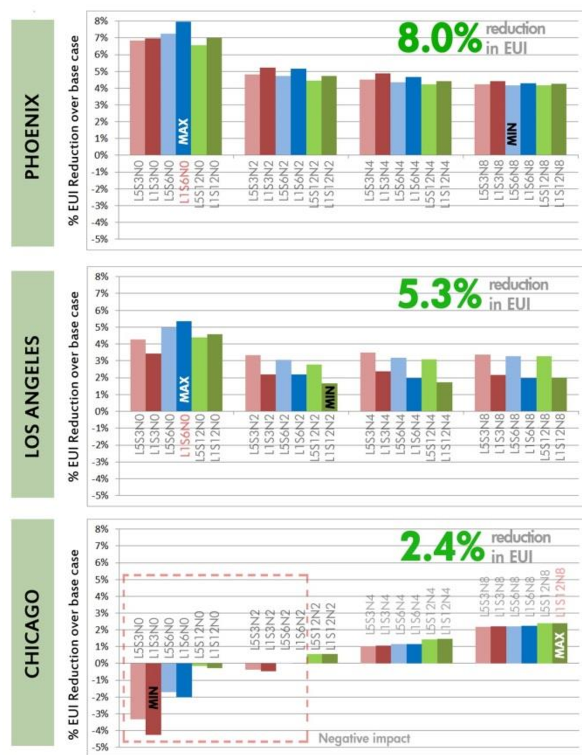


Figure 5: Comparison of EUI Reduction potential of different assemblies over base case

Insulation thickness is the parameter that affects the EUI of the building the most in Phoenix and Chicago. It increases the EUI by 1.48 kBtu/ sq.ft in Phoenix while decreases the EUI by 2.33 kBtu/ sq.ft in Chicago when insulation thickness is increased from 0” to 8”. For Los Angeles, the LAI has the largest impact, where it reduces the EUI by up to 0.48 kBtu/ sq.ft when LAI is increased from 1 to 5. The soil depth parameter affects the EUI nominally for Phoenix and Los Angeles, but for Chicago the impact of changing the soil depth is a little stronger. Also, the variance in EUI between the different green roof assemblies is more prominent in Chicago than for any other climate type.

Performance metric- Annual Heating and Cooling loads:

Green roofs are observed to be more effective in reducing the cooling loads (up to 21% over base case in Phoenix) of a building as compared to annual heating loads, for all climate types. The bar charts in Fig 6. clearly indicate the same. The strongest parameter affecting the annual cooling loads of the building is the insulation thickness for all climate types. It is also interesting to note that a larger LAI results in lower cooling loads for all climates. Theoretically, greater LAI means more shading on the roof, which in turn implies reduced solar heat gains through the roof. This would logically result in lower cooling loads that can be seen in Fig 6. Also, the variance in this metric between the different green roof assemblies is more prominent in Phoenix than for any other climate type.

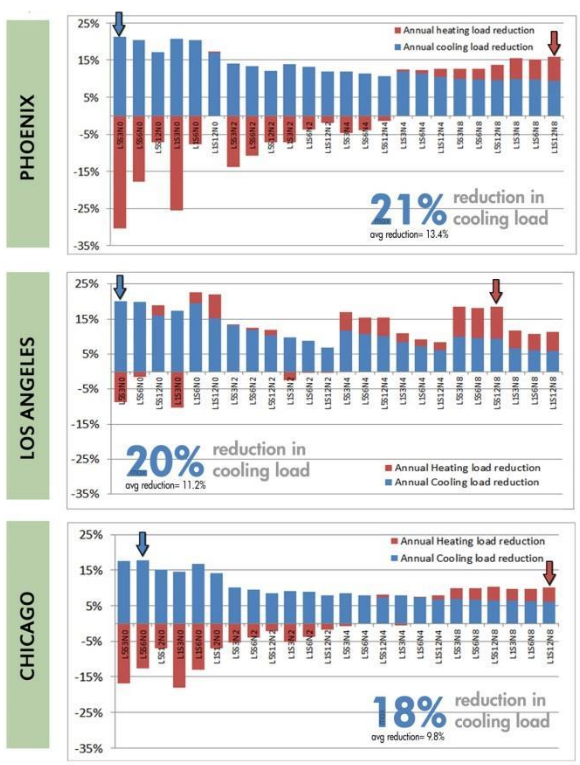


Figure 6: Comparison of annual cooling and heating load reduction potential of different green roof assemblies over base case

Overall, all the different green roof assembly types perform better than the cool roof base case with respect to the annual cooling loads, in all climate types. However, some assemblies suffer from a significant increase in the annual heating loads over the base case. Generally heating costs are much greater than cooling costs for a building (EIA 1995), so if building operational costs are a driver for assembly selection, one would be careful not to choose assembly types like L5S3N0 and L1S3N0. In such a case, it would be a better option to go with assemblies like L1S3N8 and L1S12N8 which have a relatively lower cooling load reduction potential than L5S3N0 and L1S3N0 but at least they do not cause the heating loads to increase over base case.

Performance metric- Peak Cooling Loads:

The effect of the different green roof assemblies is also observed on a diurnal scale and the correlation between the parameters is compared across the three different climate types. The peak cooling day for each climate type is noted and the peak cooling load on that day is plotted (for each green roof assembly, shown in green dot) to generate the final scatterplot matrix where the dotted line denotes base case (Fig 7).

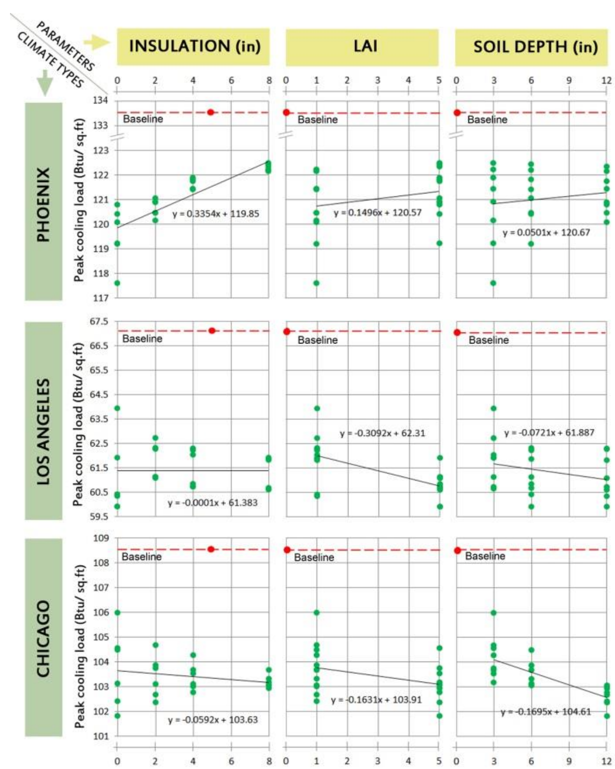


Figure 7: Parametric comparison of peak cooling loads for different green roof assemblies

The strongest parameter affecting this performance metric (as can be determined by observing the slope of the trend line) is the insulation thickness for Phoenix, LAI for Los Angeles and soil depth for Chicago. It is interesting to note that the insulation thickness has hardly any effect on this performance metric for Los Angeles. Also, for every climate type, the peak cooling load for all green roof assemblies are much lower than the base case.

Performance metric- Annual heat balance through the roof:

Significantly lower solar heat gains by the green roof assemblies are noted, when compared to the cool roof base case. Of all the assemblies, the one with maximum and minimum heat exchange over the year are selected and plotted in the graphs shown in Fig. 8. The reduction over base case is shown as a percentage, for the peak month of July, for each climate type. In Phoenix, this reduction can be up to 90% over base case.

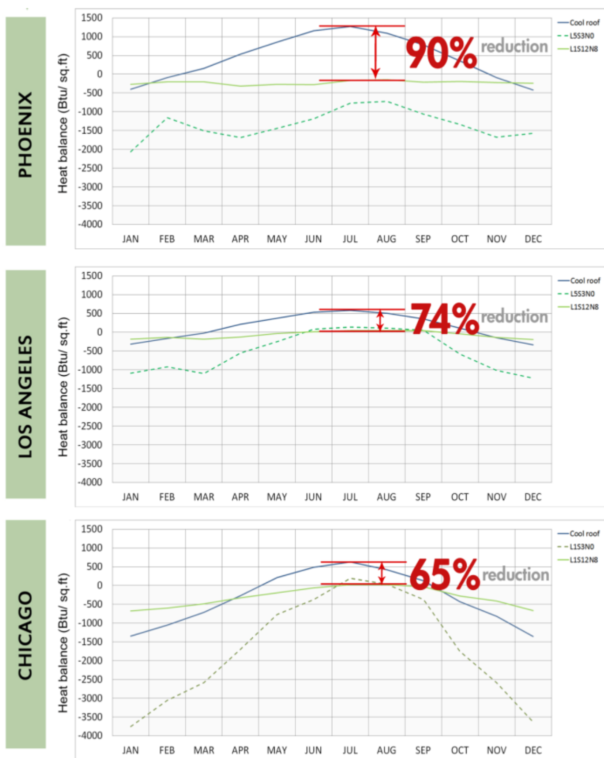


Figure 8: Comparison of annual heat balance reduction potential of different green roof assemblies over base case

The diurnal heat flux (swing) through the roof assembly over the year is also less than that of a cool roof, for most of the assemblies. Therefore the green roof has a much longer life span than a cool roof, since structural damage of the roof due to heat flux is reduced over time. This plays a big role in the life cycle costs analysis of a building, and so careful selection of assembly type is important here as well, since some of these assemblies have a greater heat flux than the cool roof, depending on the climate that is being considered.

CONCLUSION

The parametric study of the green roof assemblies shows that they have a positive thermal impact on the building and have the potential to reduce the energy use intensity of the same, in comparison to a cool roof. The extent to which it does that, however, depends on the climate type. A few conclusions that can be drawn from this parametric study are as follows-

- The strongest parameter affecting the EUI of the building for Phoenix and Chicago is the insulation thickness, although the nature of their correlation is different. For Phoenix, insulation thickness is positively correlated to EUI while for Chicago it is the reverse. For Los Angeles, the LAI parameter affects the EUI more than the other two parameters. Also, the variance in EUI between the different green roof assemblies is more prominent in Chicago than for any other climate type.

- Overall, green roofs are more effective in reducing the cooling loads of a building. Some assemblies can result in higher heating loads, so a careful selection of assembly type is important, in order to keep the building operational costs low.

- Significantly lower solar heat gains and heat flux through the roof is noted in the case of green roof assemblies, when compared to cool roofs. This impacts the lifespan of the green roof, making it 2-3 times longer than conventional roofs (Green Building Alliance, 2013), thereby resulting in lower life cycle costs.

- In case of the green roof, a thermal lag is also noted. The green roof mainly loses heat during the day and gains heat at night, as opposed to a cool roof which gains heat during the day (thereby increasing cooling loads on the building when the peak demand for electricity is high) and loses heat at night (thus increasing the heating load on the building). Due to the thermal lag provided by the green roof, the latter peaks at a time when the electricity costs are not at peak, therefore impacting the building operational costs over time.

Different parameters affect the thermal performance of the building to varying extents. The matrix in Table 1 shows the correlation (positive or negative) between the different parameters and performance metrics, for each climate type. This basically summarizes the conclusions drawn from the parametric study. The matrix tells the reader whether the metric increases or decreases on increasing or decreasing the parameter and the degree of impact that parameter has on that metric.

Table 1: Correlation between parameters and metrics

Climate type	Performance metric	Strongest parameter affecting metric: Insulation thickness	Leaf Area Index	Soil Depth
Hot-dry Phoenix	EUI	+	+	+
	Annual Cooling Loads	+	−	+
	Annual Heating Loads	−	+	−
	Peak Cooling load	+	+	+
	Peak Heating Load	−	+	−
	Annual Heat Balance (roof)	+	−	+
Warm-Coastal Los Angeles	EUI	+	−	+
	Annual Cooling Loads	+	−	+
	Annual Heating Loads	−	−	−
	Peak Cooling load	−	−	−
	Peak Heating Load	−	−	−
	Annual Heat Balance (roof)	+	−	+
Cool-Humid Chicago	EUI	−	−	−
	Annual Cooling Loads	+	−	+
	Annual Heating Loads	−	+	−
	Peak Cooling load	−	−	−
	Peak Heating Load	−	−	−
	Annual Heat Balance (roof)	+	−	+

+ Positive correlation: Metric increases with increase in parameter

− Negative correlation: Metric decreases with increase in parameter

Impact of parameter on metric: Strong to weak

There may be several other parameters of the green roof assembly that affect the thermal performance of the building, but only three of these were explored within the scope of this paper.

ACKNOWLEDGEMENTS

I gratefully acknowledge the support and guidance of Prof. Pablo La Roche. He inspired me to think and develop the research idea, as my graduate thesis chair. I would also like to thank Prof. Kyle Konis and Prof. Joon Ho Choi for their contribution in this research, as well as Jeffrey Landreth for his help with energy modeling and data interpretation and Steven Sandifer for his help with the validation study.

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