INTRODUCTION:

Paper airplanes are an important model system for studying flight. For such studies, four forces are particularly important: thrust, drag, lift, and gravity (Ng and So 2004). Lift and gravity are opposing forces that each act on different points on an aircraft called the center of lift and the center of gravity, and there exists an optimal orientation of these two points along the aircraft. More specifically, the center of gravity should be located slightly ahead of the center of lift (US FAA). In theory, experimental manipulation of the relative orientation of these points along the aircraft should result in different flight distances and potentially flight trajectories that differ in their relative stability.

Here, I studied the effect of paperclip addition on the flight distance of paper airplanes. I folded 30 paper airplanes, using R to conduct cluster random assignment to treat each plane as a cluster, each with 5 throws, for a total of 150 trials. To planes assigned treatment, I attached a paperclip near the middle of the aircraft. To planes assigned control, I did not attach a paperclip. I conducted trials in a long and skinny hallway in my New Haven apartment. I recorded flight distances in centimeters, and I also recorded whether or not planes collided with the wall during their flights.

I found that paperclip addition increased flight distances by 118.64 centimeters; this estimate decreased to 117.06 centimeters with covariate adjustment, which included throw order; both effects of paperclip addition were statistically significant, and the throw order covariate had a slightly positive, but statistically insignificant effect on flight distances. I also found that paperclip addition resulted in lower rates of wall collisions by 22.7% without covariate adjustment. This effect was statistically significant; covariate adjustment including throw order decreased this effect to 20.4%, which was no longer statistically significant, but still had a very low p-value. Throw order had a very slightly negative effect, but was again statistically insignificant.

These results suggest that paperclip addition increases flight distance for paper airplanes, and may lead to more stable flight paths. More broadly, these findings suggest that paperclip addition favorably modifies the location of the center of gravity in relation to the center of lift. The average increase in flight distance following paperclip addition found here far exceeds that found in a recent study of toothpick addition (Wang 2020). Here, I present a discussion of potential reasons why, along with potential future directions and the limitations of this study and other similar studies.

THEORY:

Paper airplanes provide an accessible way to study the physics of flight. Of course, some paper airplanes fly farther than others. The flight of any paper airplane is mediated by four forces: thrust, drag, lift and gravity (Ng and So 2004). An initial throw of a paper airplane provides thrust, propelling the aircraft forward. In flight, drag acts in the opposite direction. Lift and gravity also oppose each other: gravity pulls a paper airplane downward from a point on the aircraft called center of gravity, while lift (generated by the wings) buoys the plane from a point called the center of lift. The location of the center of lift in relation to the center of gravity is vitally important in determining the flight path of a paper airplane. For a paper airplane, which flies by gliding through the air, the optimal location of the center of gravity is slightly ahead of the center of lift (closer to the nose of the aircraft) (US FAA). When the location of these points in relation to each other is suboptimal, the flight of the paper airplane is also suboptimal. Thus, how far a paper airplane ultimately flies depends on the orientation of the center of gravity in relation to the center of lift, and modifying this relationship also likely impacts flight distances.

Flight distances also depend on objects that may impede the flight path of a paper airplane. This idea is especially relevant indoors, where furniture and walls abound**.** Indoors, erratic flight paths could lead to collisions with walls and furniture, and could consequently diminish flight distances. Theoretically, the addition of a small amount of weight to a normal lightweight paper airplane could help stabilize the aircraft in flight, preventing collisions with objects indoors and ultimately leading to larger flight distances.

Flight distances may also depend on differences between throws of the same paper airplane and differences between paper airplanes themselves. If every throw of a single paper airplane were the same, said paper airplane would always fly the same distance. Empirically, however, we know that the same paper airplane almost never flies the same exact distance twice, and there is thus variation between throws. This variation would persist even if someone throwing a paper airplane (hereafter 'thrower') tried to keep every throw the same. I suspect that a thrower trying to maximize the distance a paper airplane flies while holding a throwing motion constant would either 1) gain proficiency over time, as they became more acquainted with the paper airplane, or 2) lose proficiency over time due to fatigue, boredom, or some other factor.

Variation between paper airplanes can also affect how far they fly. There is likely also variation between paper airplanes of different designs. Different folding patterns can yield large differences in center of gravity and wing shape, which in turn will affect how forces act on the paper airplanes in flight. Variation still likely exists between paper airplanes of the same design due to minute differences in folding and wing angle. Along with variation in throws, structural damage to the same paper airplane may also affect flight distance over time.

DESIGN:

I constructed 30 paper airplanes of the same design. Each paper airplane was folded from HP Multipurpose 20 8.5” x 11” printer paper, and I wrote a number from 1 to 30 at the same spot near the back of each paper airplane. I threw each paper airplane 5 times, for a total of 150 trials, recording the order of throws in the process. I used paper airplanes as clusters to assign throws; I achieved this cluster random assignment using R, which generated 75 treatment throws and 75 control throws (with 15 plane clusters each in the treatment and control groups). For a given throw, R returned a 1 to denote assignment to treatment, and a 0 to denote assignment to control.

For clusters of throws that were assigned treatment, I attached a paperclip near the middle of each paper airplane (see Figure 1), which moved the center of gravity in relation to the center of lift. For clusters of throws assigned to control, I did not add a paperclip, which kept constant the relative locations of the center of gravity and the center of lift. I threw each paper airplane with the same motion in an effort to minimize variability and avoid an excludability violation.

Using a measuring tape, I recorded flight distances in centimeters. Trials took place indoors, which eliminated wind as a potential variable impacting flight distances. The most suitable location for trials in my New Haven apartment was a long and skinny hallway. Thus, I also recorded whether or not planes contacted a wall on either side of the hallway during flight, which may be a suitable proxy for the straightness of a given flight, facilitating a potential comparison between treatment and control groups. The two outcome measures were thus flight distance and whether or not a given throw resulted in a paper airplane contacting the wall during flight.

RESULTS:

Among paper airplanes assigned treatment, average flight distance was 481.84 centimeters; among airplanes assigned to control, average flight distance was 363.2 centimeters

(Table 1). Using a difference-in-means approach, I found that the addition of a paperclip to paper airplanes resulted in flight distances that were, on average, 118.64 centimeters farther (see Table 1). This effect was statistically significant ($p < 0.001$).

Table 1. Effect of paperclip addition on flight distance.

	term	estimate	std.error	statistic	p.value	conf.low	conf.high	df	outcome
1	(Intercept)	363.20	21.12	17.19	8.3e-11	317.89	408.50	14.00	distance
2	paperclip	118.64	29.30	4.05	0.0004	58.63	178.65	28.00	distance

Note: *paperclip* was coded as 1's (treatment) and 0's (control). Distances in centimeters.

Covariate adjustment slightly reduces the estimate of the average treatment effect to 117.06 centimeters, which is still statistically significant ($p < 0.001$) (Table 2). The covariate I included was throw order, which has a slightly positive, but statistically insignificant ($p = 0.81$) effect on flight distances (Table 2).

Table 2. Covariate-adjusted effect of paperclip addition on flight distance.

	term	estimate	std.error	statistic	p.value	conf.low	conf.high	df	outcome
1	(Intercept)	358.29	31.64	11.33	6.7e-8	289.61	426.98	12.39	distance
2	paperclip	117.06	30.45	3.84	0.0009	53.86	180.25	21.70	distance
3	throws	0.08	0.31	0.24	0.81	-0.59	0.74	14.14	distance

Note: the variable *throws* corresponds to throw order. Distances in centimeters.

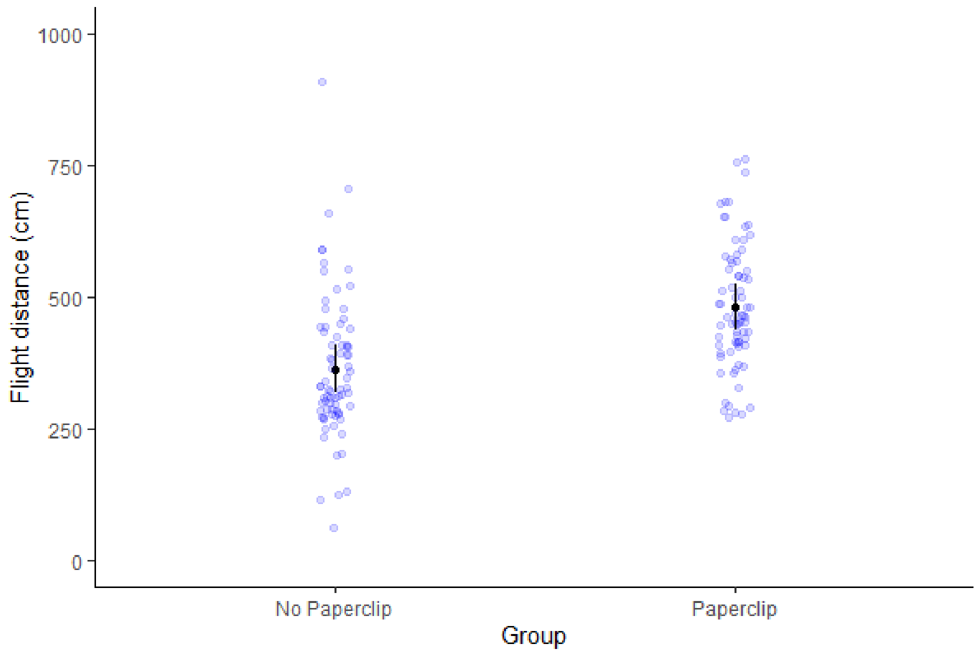

Figure 1. *This plot shows the mean flight distances in the control ("No Paperclip") and treatment ("Paperclip") groups, with error bars representing the bounds of a 95% confidence interval for each mean. Each blue point on the figure represents a distance measurement from one trial (throw).*

Using a difference-in-means approach, I found that adding a paperclip decreases the frequency with which a plane hits the wall; this effect was statistically significant ($p < 0.05$). The control group mean of the wall collision variable, which was measured in 0's (no collision) and 1's (collision), is 0.68, while the treatment group mean is 0.453; thus, the addition of a paperclip results in an average decrease in wall collision rate by 0.227 (Table 3).

Table 3. The effect of paperclip addition on wall collision rates.

	term	estimate	std.error	statistic	p.value	conf.low	conf.high	df	outcome
1	(Intercept)	0.68	0.08	9.06	3.1e-7	0.52	0.84	14.00	wall_hit
2	paperclip	-0.23	0.10	-2.18	0.04	-0.44	-0.01	28.00	wall_hit

Note: the outcome variable *wall_hit* was coded as 1's (wall collision occurred) and 0's (no wall collision occurred).

Inclusion of the throw order covariate decreased this estimate to 0.204, and actually made this predictor no longer significant, albeit still with a very low p-value ($p = 0.08$) (Table 4). The throw order covariate had a very small negative effect (0.001), and again was not statistically significant ($p = 0.31$) (Table 4).

Table 4. The covariate-adjusted effect of paperclip addition on wall collision rate.

	term	estimate	std.error	statistic	p.value	conf.low	conf.high	df	outcome
1	(Intercept)	0.75	0.10	7.85	3.7e-6	0.54	0.96	12.39	wall_hit
2	paperclip	-0.204	0.11	-1.83	0.08	-0.44	0.03	21.70	wall_hit
3	throws	-0.001	0.00	-1.06	0.31	-0.00	0.00	14.14	wall_hit

Note: the covariate in this model is throw collision rate.

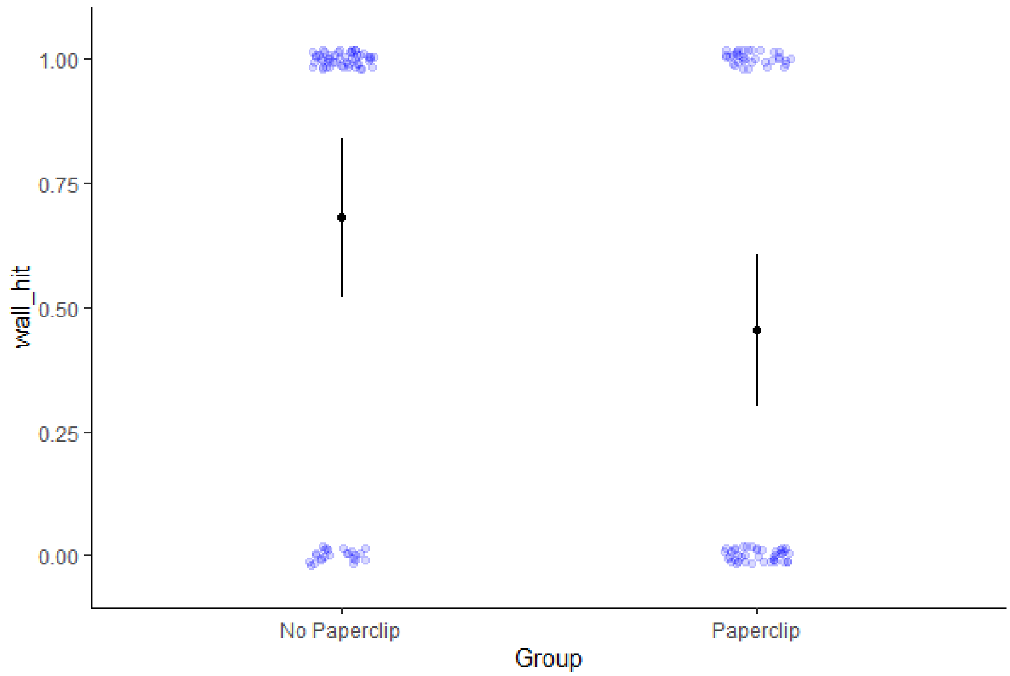

Figure 2. *This plot depicts the mean wall collision rate by control ("No Paperclip") and treatment ("Paperclip"), with error bars associated with the bounds of a 95% confidence interval for each group mean. Each blue point on the graph corresponds to a single trial (throw).*

In addition, I found that the variance between paper airplanes was similar to the variance within paper airplanes. The intra-cluster correlation coefficient (ICC), is a measure of the similarity of clustered data; ICC values close to 1 suggest that values in each cluster are quite similar (Killip et al. 2004). The calculated ICC value from this experiment is 0.49. Our findings thus suggest that between- and within-plane variances are very similar.

RECONCILIATION:

When I designed this experiment, I anticipated that the variation in flight distance between paper airplanes of the same design (inter-cluster variance) likely exceeded the variation in flight distance within specific paper airplanes (intra-cluster variance). Accordingly, I declared a design that resulted in an estimated ICC value of 0.23, suggesting higher between-plane variance relative to within-plane variance.

In the design I declared, the only measured outcome variable was flight distance. When I implemented the design, I also decided to record whether a given plane contacted the wall during flight, which at first was not an intuitive outcome measure. In addition, I declared flight distances measured in meters. Upon implementation, I measured flight distances in centimeters; of course, conversion between these two units is simple, but I thought that centimeters were a more intuitive unit for recording and subsequently reporting outcomes.

Based on a pilot study, I declared that the mean flight distance in the control group was 5 meters (500 centimeters) with an average treatment effect of 1.7 meters (170 centimeters). Both the observed mean flight distances and the average treatment effect were smaller than I anticipated. I initially planned to attach a keychain ring to planes rather than a paperclip, so I conducted the pilot study with the keychain ring, declaring flight distances accordingly. The keychain ring proved difficult to attach to paper airplanes: I feared that attachment of the keychain ring would compromise the structural integrity of the paper airplanes. Paperclip attachment was much easier; because I had to attach a weight to 15 different paper airplanes, I made the switch to a paperclip. The paperclip I used was lighter and flimsier than the keychain ring. The heavier weight of the keychain ring could have contributed to larger observed flight distances during the pilot study, and thus may explain the difference between declared and observed outcomes.

DISCUSSION:

My results suggest that the addition of a paperclip to paper airplanes increases their flight distances. Paperclip addition also results in a lower wall collision rate. The implications of this study support the theory presented here, and are twofold: first, the finding that paperclip addition increases flight distance implies favorable modification of the center of gravity in relation to the center of lift; second, the finding that paperclip addition results in a lower wall collision rate suggests that the added weight does indeed stabilize the aircraft in flight, ultimately leading to straighter flight paths.

In theory, the modification of the center of gravity in relation to the center of lift should result in larger flight distances. The observed average increase in flight distance from this study is quite large. One similar study evaluated the effect of toothpick addition on flight distance, finding a 7.7-centimeter increase in flight distance with toothpick addition (Wang 2020). Our observed average increase in flight distance with paperclip addition is 118.64 centimeters without covariate adjustment, and is 117.06 centimeters with covariate adjustment. Both of these average increases are far greater than that presented in Wang (2020). In Wang (2020), toothpicks were placed in the centerfold of each paper airplane, which suggests that added weight was relatively spread out throughout the aircraft, while paperclip addition resulted in a more localized addition of weight. These differences suggest that paperclip addition more effectively modifies the center of gravity in relation to the center of lift than does toothpick addition.

Future studies should compare the effects of paperclip and toothpick addition on flight distances for paper airplanes of the same design. The possibility remains that some paper airplane designs are more responsive than others to each treatment, or that some throwing motions result in more favorable responses to treatment. Studying these treatments in tandem will allow researchers to disentangle the true effects of each relative to each other by standardizing other aspects of the design, including paper airplane design and throwing motion.

I recorded wall collisions during this study because I was confined to a long and skinny hallway in my apartment. I found lower wall collision rates on paper airplanes in the treatment group, those with paper clips added. In turn, wall collisions likely cut flights short. More open indoor spaces present an intriguing possibility for extension in which researchers could study the effect of paperclip addition on flight distances without walls in close proximity, and therefore without the constraint of wall collisions.

Wang (2020) also offers some important considerations and future directions for studying the flight distances of paper airplanes that are still relevant here. Because I was the only researcher running this experiment, I was aware of treatment status throughout. This knowledge may have resulted in research bias, in which I subconsciously tried to make paper airplanes assigned to treatment travel farther than those assigned to control. To address research bias, Wang (2020) suggests blinding the study, which is a valuable idea in theory; when the treatment is adding a paperclip or a toothpick, however, planes assigned to treatment are inherently distinguishable from planes assigned to control. Thus, in practice, blinding the study is likely not a possibility. An alternative approach would be constructing a contraption that would launch paper airplanes in an unbiased manner (Wang 2020), which itself presents a host of design and funding challenges.

This study also answers the call for testing the effect of a different weight on flight distances, and also increases the sample size from 90 trials to 150 trials (Wang 2020). Future efforts could further assess different weights with even larger sample sizes, with potential extension to studying flight distances among paper airplanes constructed from other materials. Overall, this study finds that paperclip addition makes paper airplanes fly farther and decreases the rate at which planes hit the wall in a long and skinny hallway, which suggests that paper airplanes with added paperclips may fly straighter than those without. These findings imply that paperclip addition favorably alters the center of gravity of a paper airplane in relation to the center of lift.

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