Supplementary Material - Adults and children predict in complex and variable referential contexts

Contents

Abstract

Prior research suggests that prediction supports language processing and learning. However, the ecological validity of such findings is unclear because experiments usually include constrained stimuli. While theoretically suggestive, previous conclusions will be largely irrelevant if listeners cannot generate predictions in response to complex and variable perceptual input. Taking a step toward addressing this limitation, three eye-tracking experiments evaluated how adults ($N = 72$) and 4- and 5-year-old children ($N = 72$) generated predictions in contexts with complex visual stimuli (Experiment 1), variable speech stimuli (Experiment 2), and both concurrently (Experiment 3). Results indicated that listeners generated predictions in contexts with complex visual stimuli or variable speech stimuli. When both were more naturalistic, listeners used informative verbs to generate predictions, but not adjectives or number markings. This investigation provides a test for theories claiming that prediction is a central learning mechanism, and calls for further evaluations of prediction in naturalistic settings.

Experiment 1

Mixed Effects Models

The omnibus mixed effects model includes an interaction of age (adults vs. children), condition (predictive vs. neutral), and time (-1000 to 1000 ms from noun onset; 100 ms time-bins), with random intercepts for subjects and for items. We find...

term	estimate	statistic	p.value	sig
Intercept	0.298	0.91	0.379	
Condition	-0.477	-13.87	< 0.001	*
Age	0.328	3.83	< 0.001	*
Time	1.243	22.41	< 0.001	*
Condition x Age	0.038	1.12	0.262	
Condition x Time	-0.170	-3.07	0.002	*
Age x Time	0.344	6.21	< 0.001	*
Condition x Age x Time	0.140	2.53	0.012	*

For adults, we find:

term	estimate	statistic	p.value	sig
Intercept	0.623	2.22	0.049	*
Condition	-0.429	-9.12	< 0.001	*
Time	1.589	20.66	< 0.001	*
Condition x Time	-0.029	-0.38	0.707	

For children, we find:

| term	estimate	statistic	p.value	sig
Intercept	0.020	0.05	0.962	
Condition	-0.513	-10.28	< 0.001	*
Time	0.896	11.15	< 0.001	*
Condition x Time	-0.302	-3.76	< 0.001	*

Cluster-Based Permutation Analyses

To further evaluate differences in looking behavior between predictive trials and neutral trials, we used cluster-based permutation analyses (Maris & Oostenveld, 2007). We analyzed looking behavior during a time window from 1000 ms before and after the onset of the target noun. If participants used informative cues to predict the upcoming target noun, then we expected them to generate anticipatory eye movements towards the target referent before it is named, thus having greater target looks for predictive trials as compared to neutral trials. We calculated participants' mean proportion of looks to the target referent within each 100-ms time bin and performed a log-odds transformation on these proportions (Bar, 2008; Wittenberg, Khan & Snedeker, 2017). For each 100-ms time bin, we conducted a linear regression analysis on the log-odds of looking to the target referent, identified clusters of time bins (defined as 2 or more adjacent time bins with t-values greater than 1.6, as in Wittenberg, Khan & Snedeker, 2017), and summed t-values within each cluster. Next, we permuted the data to create the null distribution: We randomly shuffled condition labels 1000 times for each time bin, sampling across all time bins, and repeated the cluster-finding procedure and summation of t-values with this permuted data. Finally, we calculated the p-value for each cluster, defined as the proportion of permuted cluster t-values that were greater than the observed cluster t-value. The below tables summarize results for adults and children, respectively.

start	end	cluster.stat	pval
-600	800	41.68923	< 0.001

start	end	cluster.stat	pval
-300	1000	39.45939	< 0.001

Results by Age Group
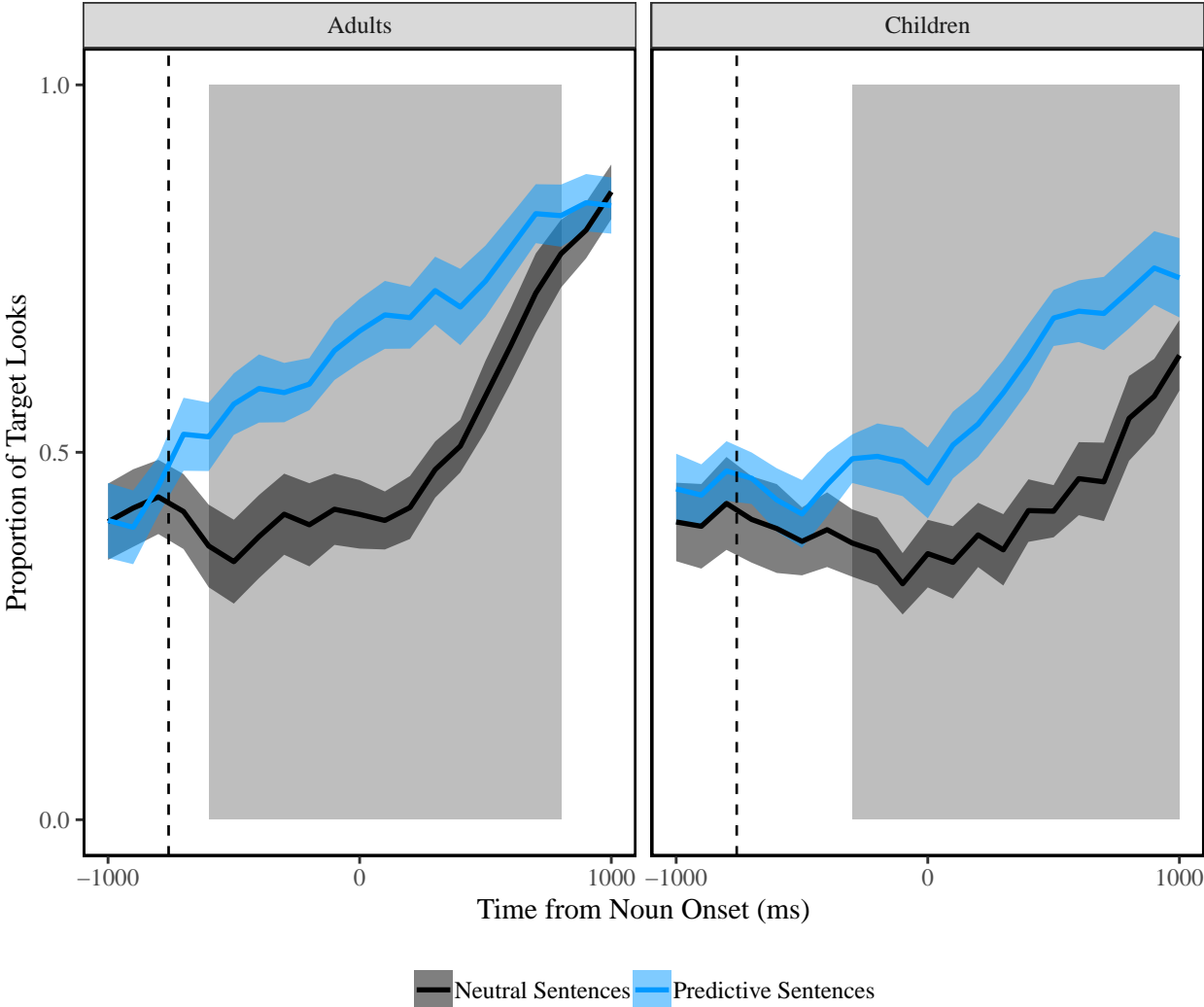
Experiment 2

Mixed Effects Models

As in Experiment 1, the omnibus mixed effects model includes an interaction of age (adults vs. children), condition (predictive vs. neutral), and time (-1000 to 1000 ms from noun onset; 100 ms time-bins), with random intercepts for subjects and for items. We find...

term	estimate	statistic	p.value	sig
Intercept	1.365	11.75	< 0.001	*
Condition	-0.401	-21.69	< 0.001	*
Age	0.252	4.36	< 0.001	*
Time	1.771	57.96	< 0.001	*
Condition x Age	-0.035	-1.89	0.058	
Condition x Time	0.258	8.46	< 0.001	*
Age x Time	0.450	14.74	< 0.001	*
Condition x Age x Time	0.011	0.37	0.709	

For adults, we find: (Note, the maximal model for adults - including random intercepts for both subjects and items - failed to converge. We therefore reduced the random effects structure and compared model fits, with the final model including only random intercepts for items.)

term	estimate	statistic	p.value	sig
Intercept	1.608	11.67	< 0.001	*
Condition	-0.440	-19.08	< 0.001	*
Time	2.221	58.24	< 0.001	*
Condition x Time	0.270	7.07	< 0.001	*

For children, we find:

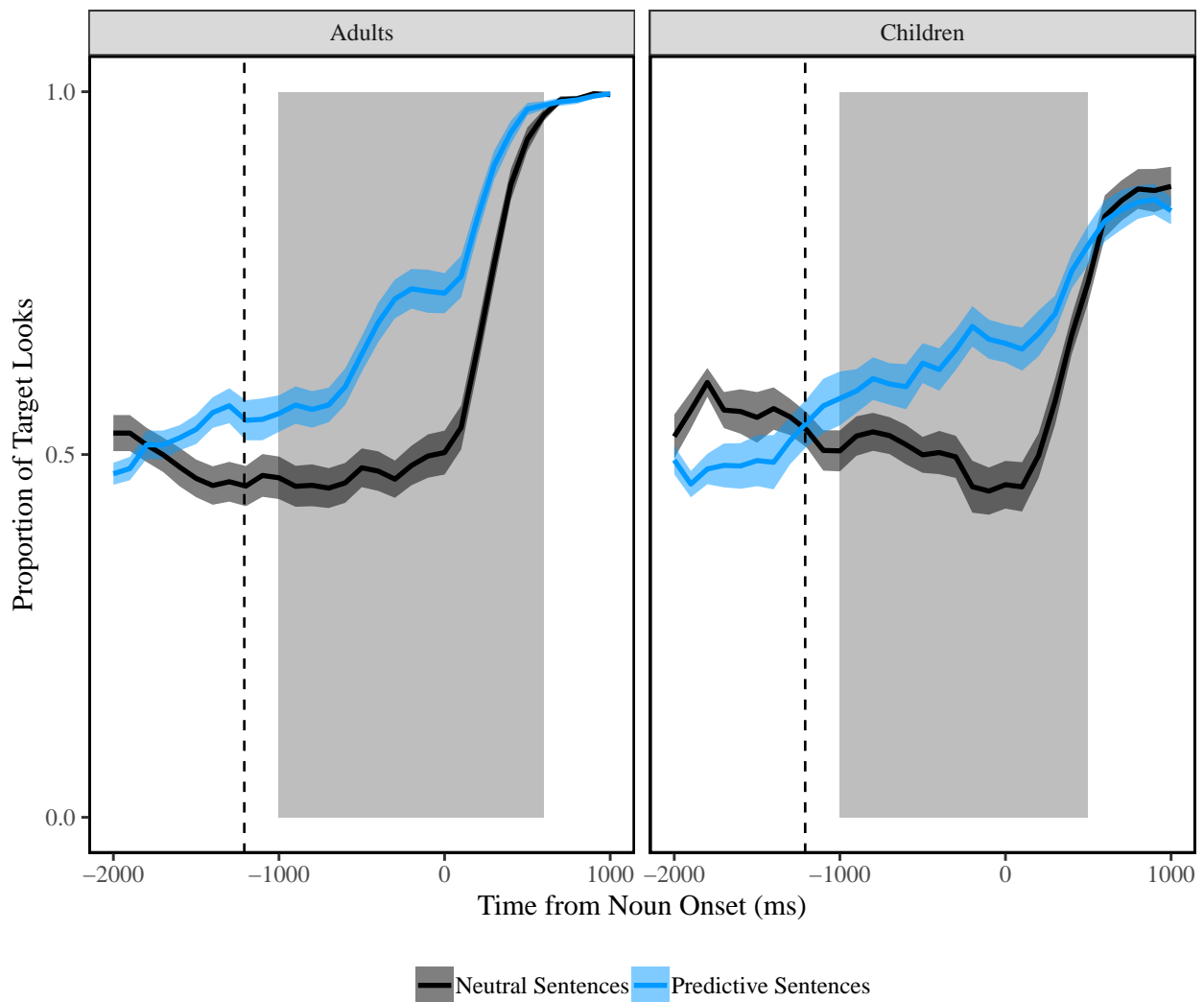| term	estimate	statistic	p.value	sig
Intercept	1.114	8.65	< 0.001	*
Condition	-0.363	-12.24	< 0.001	*
Time	1.317	26.91	< 0.001	*
Condition x Time	0.250	5.11	< 0.001	*

Cluster-Based Permutation Analyses

As in Experiment 1, we used cluster-based permutation analyses to further evaluate looking behavior. The below tables summarize results for adults and children, respectively.

start	end	cluster.stat	pval
-1000	600	77.15396	< 0.001

start	end	cluster.stat	pval
-1000	500	54.29502	< 0.001

Results by Age Group

Mixed Effects Models by Predictive Cue

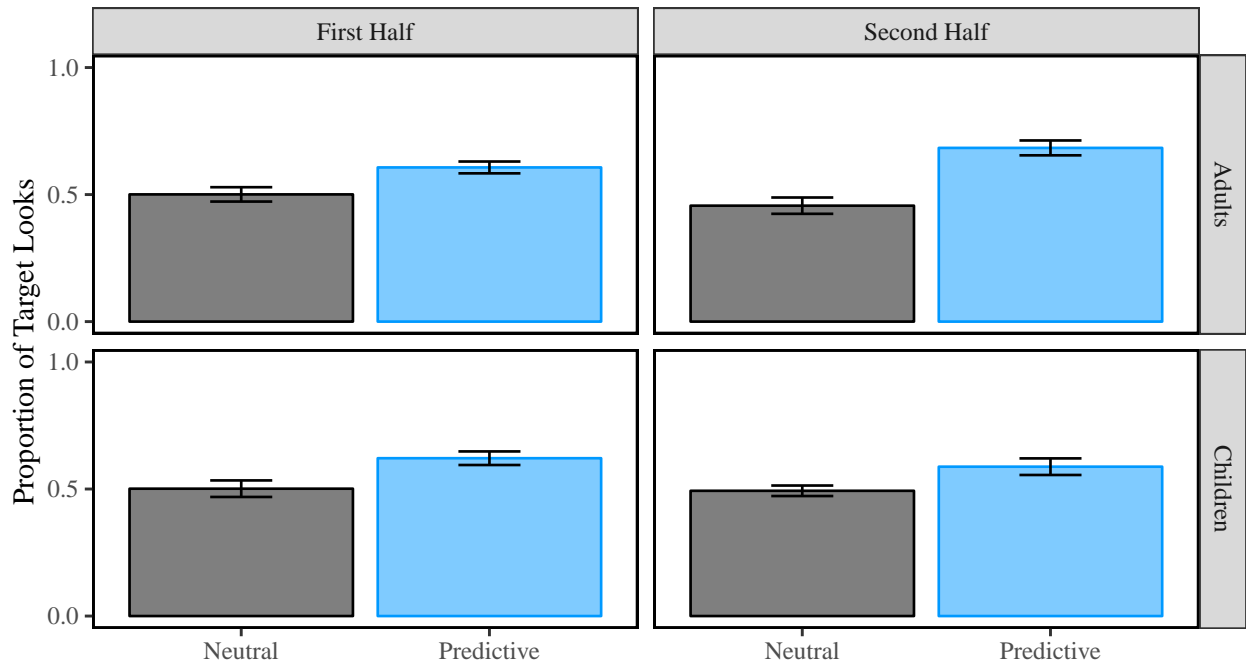| term	estimate	statistic	p.value	sig	age.group	comparison
Intercept	-0.082	-0.27	0.791		Adults	verb
Conditon	2.361	10.59	< 0.001	*	Adults	verb
Time	0.258	1.53	0.125		Adults	verb
Condition x Time	1.781	4.73	< 0.001	*	Adults	verb
Intercept	-0.079	-0.26	0.8		Adults	is/are
Conditon	1.511	6.75	< 0.001	*	Adults	is/are
Time	0.258	1.53	0.127		Adults	is/are
Condition x Time	0.642	1.69	0.09		Adults	is/are
Intercept	-0.069	-0.25	0.804		Adults	that/those
Conditon	1.547	6.96	< 0.001	*	Adults	that/those
Time	0.258	1.50	0.134		Adults	that/those
Condition x Time	1.320	3.51	< 0.001	*	Adults	that/those
Intercept	-0.082	-0.27	0.787		Adults	big/little
Conditon	2.098	9.54	< 0.001	*	Adults	big/little
Time	0.251	1.48	0.139		Adults	big/little
Condition x Time	1.400	3.76	< 0.001	*	Adults	big/little
Intercept	-0.189	-0.70	0.489		Children	verb
Conditon	2.249	9.21	< 0.001	*	Children	verb
Time	-0.382	-1.97	0.049	*	Children	verb
Condition x Time	1.181	2.85	0.004	*	Children	verb
Intercept	-0.237	-1.08	0.287		Children	is/are
Conditon	1.233	4.93	< 0.001	*	Children	is/are
Time	-0.397	-1.98	0.048	*	Children	is/are
Condition x Time	0.878	2.09	0.037	*	Children	is/are
Intercept	-0.174	-0.71	0.482		Children	that/those
Conditon	1.115	4.14	< 0.001	*	Children	that/those
Time	-0.370	-1.85	0.065		Children	that/those
Condition x Time	0.590	1.29	0.197		Children	that/those
Intercept	-0.193	-0.69	0.495		Children	big/little
Conditon	1.264	4.94	< 0.001	*	Children	big/little
Time	-0.369	-1.87	0.062		Children	big/little
Condition x Time	1.355	3.14	0.002	*	Children	big/little

Results by Predictive Cue

(Grey shading indicates significant clusters from permutation analyses.)
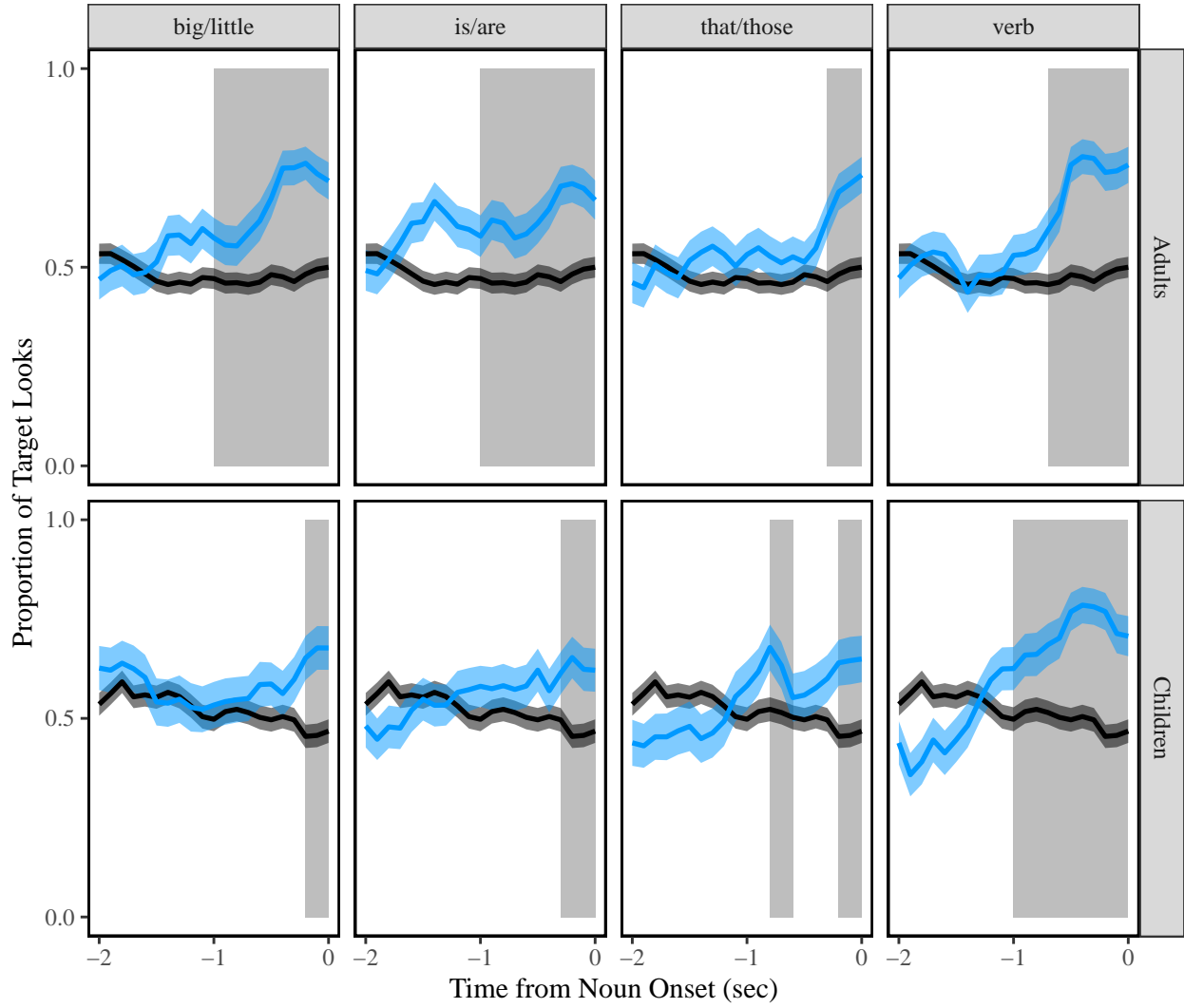
Results by Halves

As part of our response to reviewers, we conducted a post-hoc analysis of results by the first vs. second halves of trials.

term	estimate	statistic	p.value	sig
Intercept	0.381	2.82	0.013	*
Half	0.002	0.03	0.975	
Condition	-0.487	-7.12	< 0.001	*
Age	0.011	0.16	0.873	
Half x Condition	0.027	0.37	0.712	
Half x Age	-0.078	-1.14	0.256	
Condition x Age	-0.093	-1.35	0.176	
Half x Condition x Age	0.103	1.50	0.134	

For adults, we find:

term	estimate	statistic	p.value	sig
Intercept	0.399	1.97	0.065	
Half	-0.046	-0.47	0.638	
Condition	-0.579	-6.26	< 0.001	*
Half x Condition	0.168	1.67	0.095	

For children, we find:

| term	estimate	statistic	p.value	sig
Intercept	0.366	2.66	0.018	*
Half	0.045	0.44	0.657	
Condition	-0.398	-4.06	< 0.001	*
Half x Condition	-0.079	-0.77	0.444	

Results by First Predictive Occurrence

As part of our response to reviewers, we conducted a post-hoc analysis of results by the first occurrence of a yoked pair of stimuli in the predictive condition. (Grey shading indicates significant clusters from permutation analyses.)
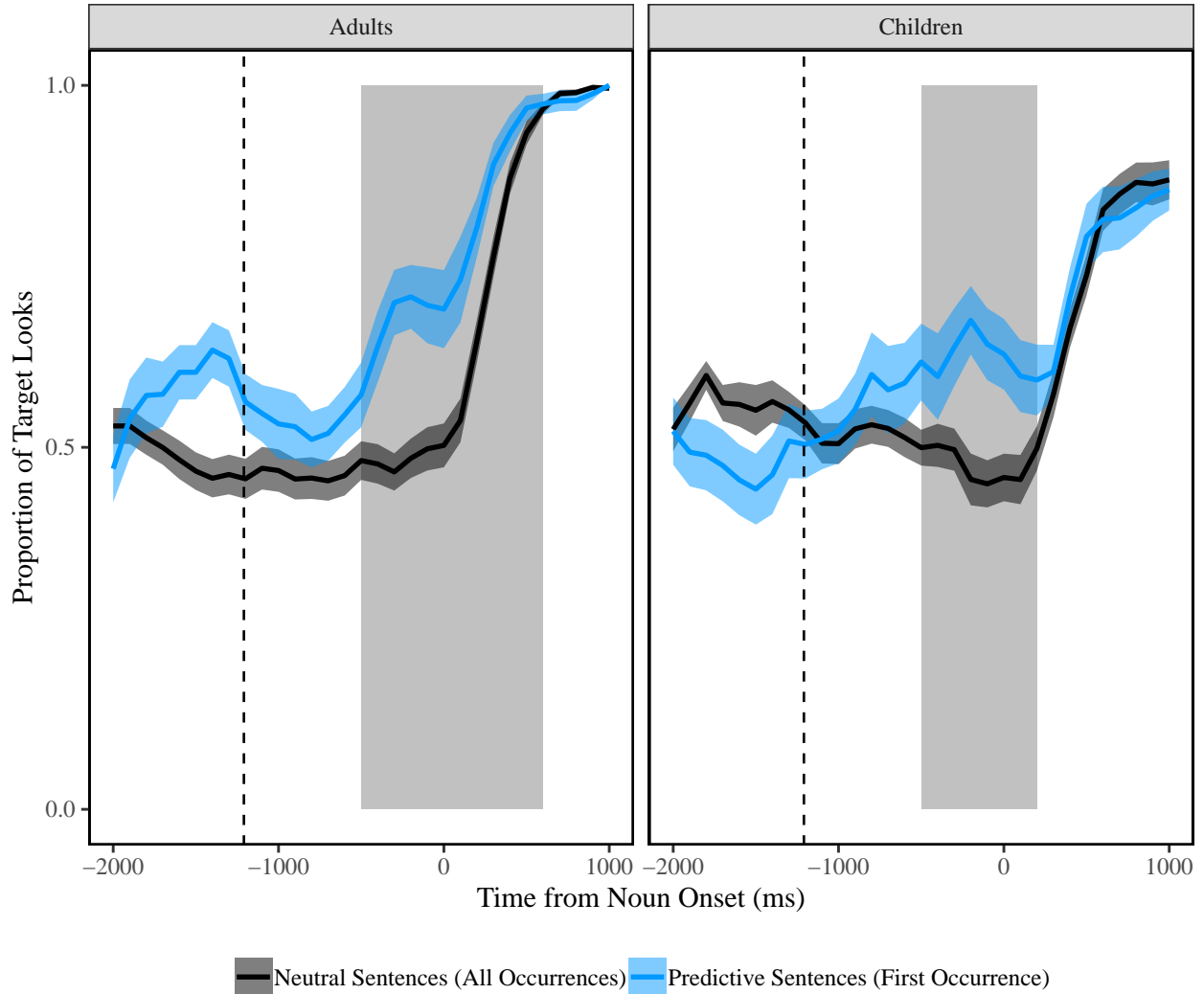
Results by Chronological Trial

As part of our response to reviewers, we conducted a post-hoc analysis of results by chronological trial order.
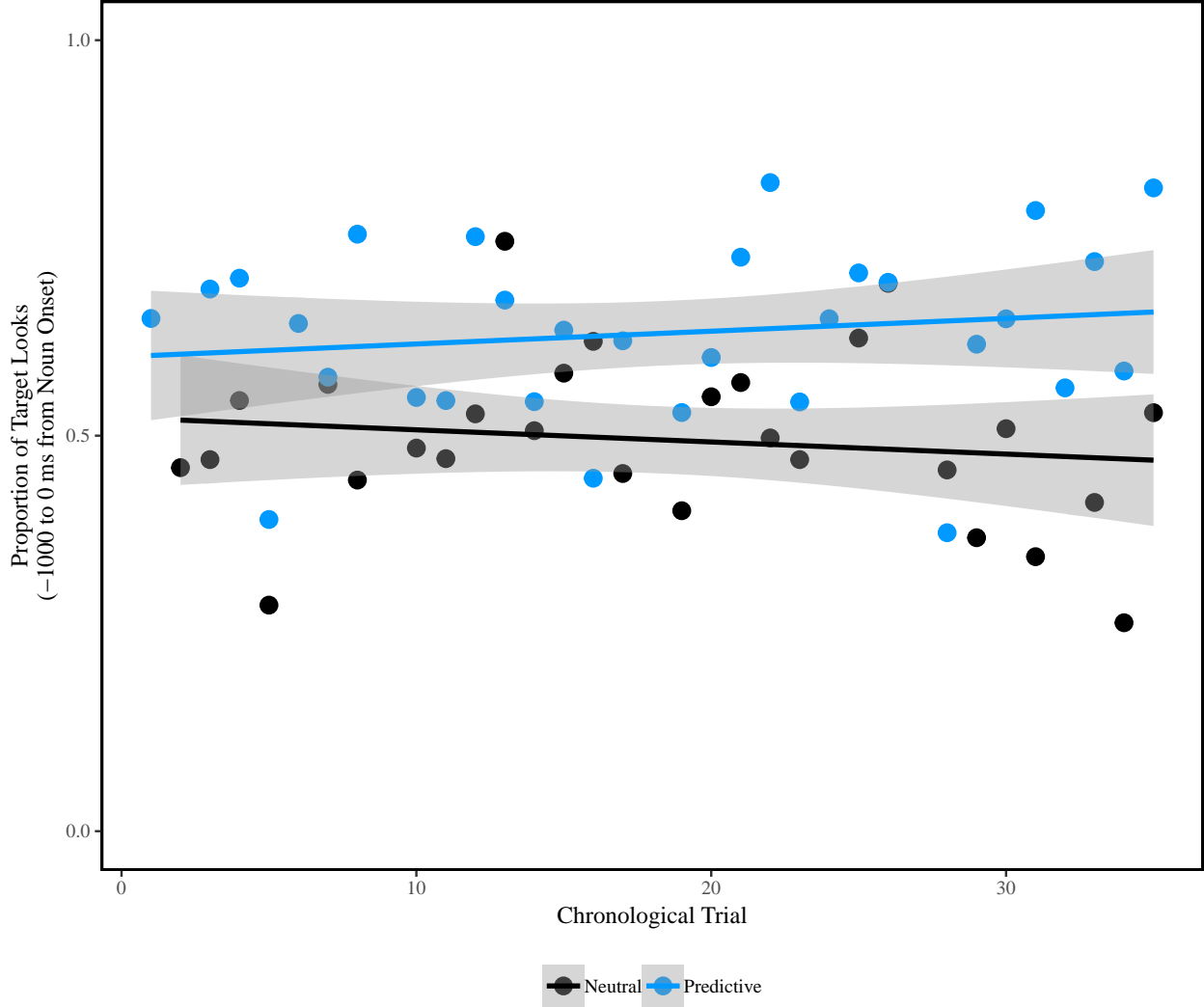
Experiment 3

Mixed Effects Models

As in Experiments 1 and 2, the omnibus mixed effects model includes an interaction of age (adults vs. children), condition (predictive vs. neutral), and time (-1000 to 1000 ms from noun onset; 100 ms time-bins), with random intercepts for subjects and for items. We find...

term	estimate	statistic	p.value	sig
Intercept	-0.178	-0.71	0.497	
Condition	-0.088	-4.59	< 0.001	*
Age	0.377	5.16	< 0.001	*
Time	2.427	76.45	< 0.001	*
Condition x Age	0.030	1.56	0.119	
Condition x Time	0.057	1.79	0.074	
Age x Time	0.359	11.30	< 0.001	*
Condition x Age x Time	0.058	1.84	0.066	

For adults, we find:

term	estimate	statistic	p.value	sig
Intercept	0.198	1.00	0.336	
Condition	-0.058	-2.44	0.015	*
Time	2.786	70.70	< 0.001	*
Condition x Time	0.115	2.93	0.003	*

For children, we find: (Note, the maximal model for children - including random intercepts for both subjects and items - failed to converge. We therefore reduced the random effects structure and compared model fits, with the final model including only random intercepts for items.)

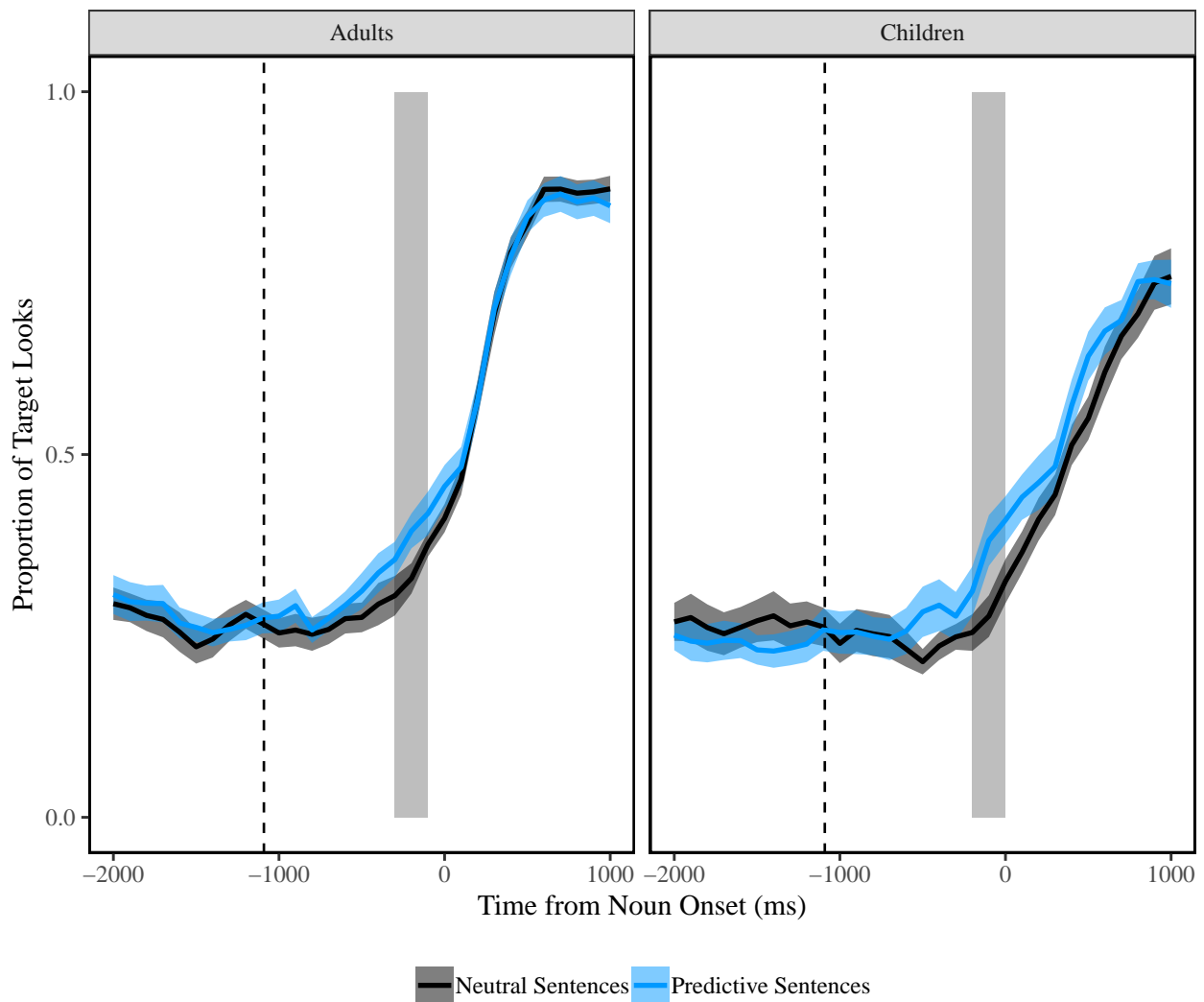| term	estimate	statistic	p.value	sig
Intercept	-0.554	-1.63	0.147	
Condition	-0.123	-3.98	< 0.001	*
Time	2.060	40.45	< 0.001	*
Condition x Time	0.005	0.10	0.923	

Cluster-Based Permutation Analyses

As in Experiments 1 and 2, we used cluster-based permutation analyses to further evaluate looking behavior. The below tables summarize results for adults and children, respectively.

start	end	cluster.stat	pval
-300	-100	4.920749	0.027

start	end	cluster.stat	pval
-200	0	5.838534	0.005

Results by Age Group

Mixed Effects Models by Predictive Cue

term	estimate	statistic	p.value	sig	age.group	comparison
Intercept	-0.922	-3.38	0.004	*	Adults	verb
Conditon	2.031	11.52	< 0.001	*	Adults	verb
Time	1.101	6.61	< 0.001	*	Adults	verb
Condition x Time	2.256	7.58	< 0.001	*	Adults	verb
Intercept	-0.926	-3.83	0.001	*	Adults	is/are
Conditon	0.072	0.41	0.681		Adults	is/are
Time	1.101	6.51	< 0.001	*	Adults	is/are
Condition x Time	-0.404	-1.36	0.173		Adults	is/are
Intercept	-0.920	-3.06	0.008	*	Adults	that/those
Conditon	0.307	1.80	0.073		Adults	that/those
Time	1.101	6.75	< 0.001	*	Adults	that/those
Condition x Time	0.266	0.92	0.358		Adults	that/those
Intercept	-0.922	-4.09	< 0.001	*	Adults	big/little
Conditon	-0.710	-4.11	< 0.001	*	Adults	big/little
Time	1.101	6.70	< 0.001	*	Adults	big/little
Condition x Time	-1.081	-3.70	< 0.001	*	Adults	big/little
Intercept	-1.593	-4.33	0.001	*	Children	verb
Conditon	2.240	10.65	< 0.001	*	Children	verb
Time	0.384	2.02	0.043	*	Children	verb
Condition x Time	2.366	6.68	< 0.001	*	Children	verb
Intercept	-1.613	-4.50	0.001	*	Children	is/are
Conditon	-0.275	-1.40	0.162		Children	is/are
Time	0.373	2.08	0.038	*	Children	is/are
Condition x Time	0.105	0.32	0.751		Children	is/are
Intercept	-1.602	-4.22	0.002	*	Children	that/those
Conditon	0.250	1.17	0.243		Children	that/those
Time	0.369	1.97	0.049	*	Children	that/those
Condition x Time	-0.198	-0.55	0.583		Children	that/those
Intercept	-1.616	-4.37	0.002	*	Children	big/little
Conditon	0.386	1.86	0.062		Children	big/little
Time	0.370	2.02	0.044	*	Children	big/little
Condition x Time	0.740	2.12	0.034	*	Children	big/little

Results by Predictive Cue

(Grey shading indicates significant clusters from permutation analyses.)
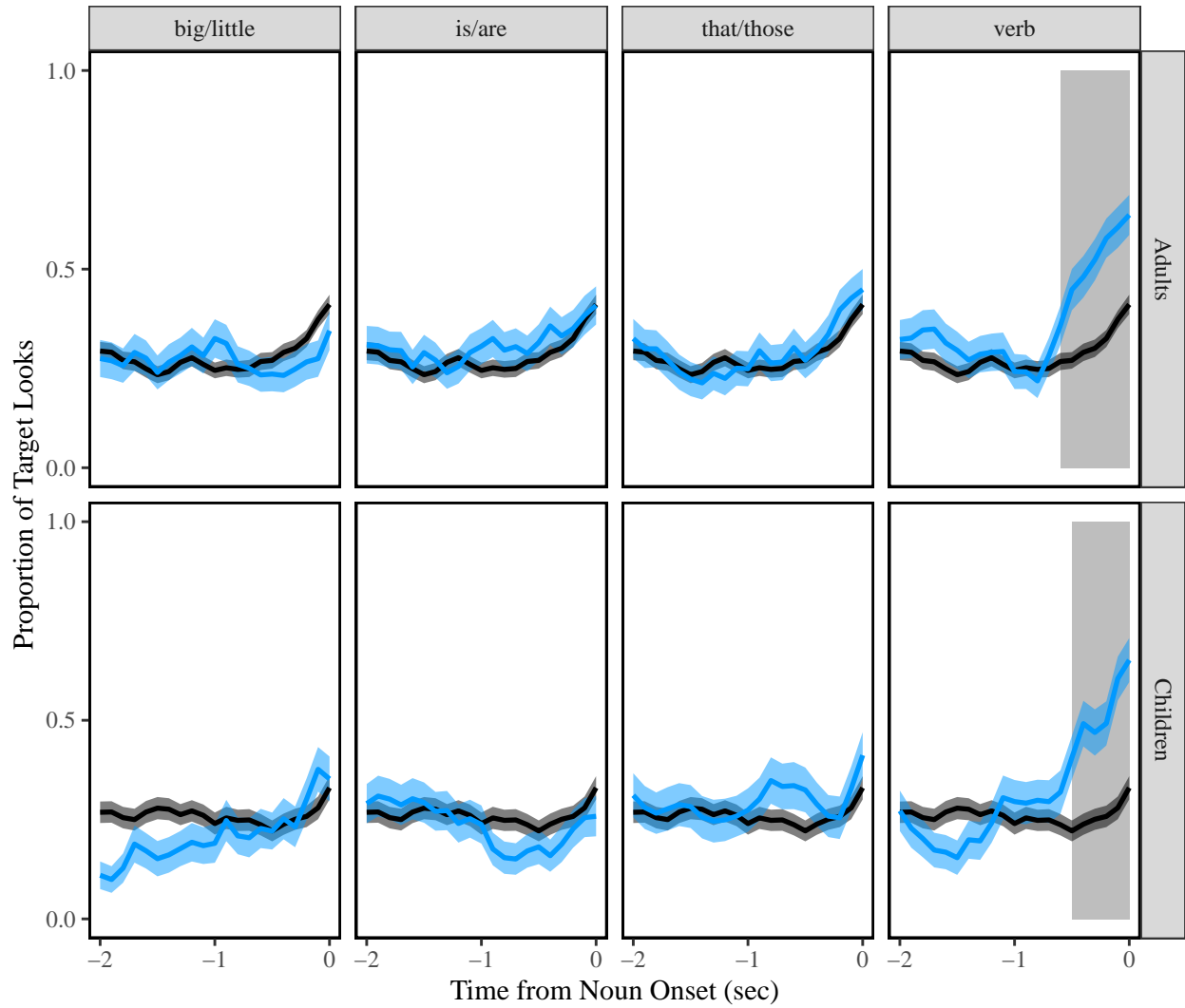
Experiment 2 Results vs. Experiment 3 Results

lmer to compare effect (predictive minus neutral) across experiments

term	estimate	statistic	p.value	sig
Intercept	0.892	13.86	< 0.001	*
Condition	0.511	12.58	< 0.001	*
Time	1.797	37.87	< 0.001	*
Experiment	-1.048	-25.29	< 0.001	*
Condition x Time	-0.291	-4.34	< 0.001	*
Condition x Experiment	-0.378	-6.57	< 0.001	*
Time x Experiment	-0.039	-0.58	0.559	
Condition x Time x Experiment	0.267	2.82	0.005	*