Quantifiers and visual cognition: the processing of proportional and superlative *most* in Bulgarian and Polish

Barbara Tomaszewicz

University of Southern California

btomasze@usc.edu

Abstract. I provide experimental evidence that quantifier semantics guides visual verification processes (Lidz et al. 2011). I tested the processing of two majority quantifiers in Bulgarian and Polish: the proportional Most1, the counterpart of English *most,* and the superlative/relative Most2. Three obtained notable results have been obtained: (i) Most1 is verified by a Subtraction strategy, directly replicating the findings of Lidz et al. for Slavic; (ii) Most2 is verified by a Selection strategy in accordance with its lexical semantics; (iii) each verification strategy is consistently used even in cases where either strategy would yield the correct truth value.

1 Introduction

Lidz et al. (2011) argue that the verification of truth/falsity a declarative sentence is biased towards those procedures that are transparently associated with the semantic representation of that sentence. They show that sentences containing the quantifier *most* such as (1) are uniquely associated with truth conditions and a verification procedure involving subtraction (2), despite the availability of other semantically equivalent specifications (e.g. 3).

1. Most of the dots are yellow.
2. |Dot(x) & Yellow(x)| > |Dot(x)| – |Dot(x) & Yellow(x)|
3. |Dot(x) & Yellow(x)| > |Dot(x) & Red(x)| + |Dot(x) & Blue(x)| + |…|

I provide further experimental evidence that quantifier semantics guides the verification process. My evidence is based on the comparison of the verification patterns of two minimally distinct quantifiers and suggests that the properties of the linguistic input directly influence the unconscious visual processes.

The meaning of *most* intuitively refers to a comparison of quantities, where one of the quantities is greater than others. For countable objects what is compared are cardinalities. Visual perception of numerical information has been studied extensively and it is known in psychology that the visual selection of a target "can be influenced by expectations and strategies" (Trick, 2008). Manipulating a linguistic stimulus affects the patterns of the visual search for obtaining a cardinality (or its estimation), however, at the same time the choice of the visual verification strategy is also constrained by the psychophysics of visual cognition. We can both formulate hypotheses and interpret the visual response pattern on the basis of the findings about human perception in visual numerical judgment tasks. Under time pressure, when precise counting becomes impossible, people switch to the Approximate Number System (ANS) that generates a representation of magnitude and is governed by Weber's law, i.e. the greater the distance between two numbers the better discriminability (Dehaene, 1997). Numbers can be represented as 'noisy magnitudes' even for the purposes of basic arithmetic operations like addition and subtraction. Quantifiers can be verified against a visual display even when counting is blocked.[1] Psychophysical constraints, however, affect the accuracy of judgment.

Lidz et al. (2011) hypothesize that the procedure in (3) (selection of each individual color set in order to obtain the cardinality of the non-yellow set) should be computationally costly if the verification involves more than one non-yellow set, because of the evidence from Halberda et al. (2006) that on a 500ms display, multiple color sets can be enumerated in parallel, but only for the total set of dots and two color subsets. The procedure in (3) involves selection of each individual color set in order to obtain the cardinality of the non-yellow set. The subtraction procedure in (2), on the other hand, is independent of the number of color sets and is thus more suitable as a general verification strategy for the quantifier *most*.

I argue, however, that the choice of the procedure (2) over (3) for the verification of the English quantifier *most* is not forced by psychophysics. My evidence suggests that (3) is psychologically available as a procedure for visual verification, because a computationally similar procedure is employed by the speakers of Bulgarian (Bg) and Polish (Pl) when verifying the superlative majority quantifiers *naj-mnogo* (Bg) and *najwięcej* (Pl), cf. (4).

4. |Dot(x) & Yellow(x)| > |Dot(x) & Red(x)|,
   & |Dot(x) & Yellow (x)| > |Dot(x) & Blue(x)|,
   & |Dot(x) & Yellow (x)| > |Dot(x) & Green(x)|, & …

I tested the processing of two majority quantifiers in Bulgarian and Polish: the counterpart of English proportional majority quantifier *most* (*povečeto* in Bg, większość in Pl, henceforth Most1) and a superlative/relative majority quantifier (*naj-mnogo* in Bg, *najwięcej* in Pl, henceforth Most2). I obtained three notable results:

[1] Also Halberda, Taing and Lidz (2008) have shown that children who have not yet learned to count are perfectly able to understand sentences containing *most*.

- Most1 is verified by a Subtraction strategy as in (2) and not (3), directly replicating the findings of Lidz et al. for Slavic;
- Most2 is verified by a Selection strategy as in (4) in accordance with its lexical semantics;
- Each verification strategy remains to be used even in cases where either strategy would yield the correct truth-value.

The results have some immediate implications for the semantics of quantifiers and the interface of semantics with visual cognition. We can argue for the contribution of the individual morphemes not only to the meaning of Most1 vs Most2 but also to the interface with the visual cognition. The combined Bulgarian and Polish results further strengthen the conclusions I presented in Tomaszewicz (2011) that quantifier semantics provides a set of instructions to visual verification processes, since each of the two Polish Most1 and Most2 biases a distinct verification strategy.

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2 Previous research

Pietroski et al. (2008), Lidz et al. (2011) devised experimental paradigms to look "beyond" the truth conditions of (1) to see how the meaning of a sentence containing *most* constrains the way people verify it against a visual scene. The two semantic specifications in (5) are truth conditionally equivalent, but they differ in how the cardinality of the non-yellow set of dots is arrived at. (5a) expresses a comparative relation between the cardinalities of two sets, while (5b) is a one-to-one correspondence function that maps an ordered pair of sets (X, Y) to a truth value.

5. (a) $|Dot(x)\&Yellow(x)|>|Dot(x)\&{\sim}Yellow(x)|$
   (b) $\mathit{OneToOnePlus}(\{Dot(x)\&Yellow(x)\},\{Dot(x)\&{\sim}Yellow(x)\})$

Pietroski et al. (2008) obtained evidence that even when the arrangement of dots favors the verification by strategy in (5b) (i.e. paired vs. unpaired arrangements of dots in two colors), this strategy is not used. Using the same experimental paradigm requiring visual verification under time pressure (screens displayed for 150 ms), Lidz et al. (2011) investigated how the cardinality of the non-yellow set in (5a) is estimated when this set contains dots in 1-4 different colors. They tested which of the two specifications in (6-7) *most* is verified with.

6. Selection strategy
   $|\{Dot(x)\&Red(x)\} \cup \{Dot(x)\&Blue(x)\} \cup \{Dot(x)\&Green(x)\} \cup \ldots|$
7. Subtraction strategy
   $|Dot(x)| - |Dot(x)\&Yellow(x)|$

Their proposed Subtraction strategy is based on the psychological evidence that a heterogeneous set is not automatically selectable (i.e. red, green, blue dots are not automatically processed as one set unless it is the total set of dots), as well as on the findings of Halberda et al. (2006) that humans can automatically (i.e. without a prompt) compute the total number of dots and two color subsets but no more. Thus, Subtraction in (7) does not depend on the number of colors of dots, while Selection in (6) should.

In the experiment of Lidz et al. (2011) screens with dots in up to 5 colors in varying ratios (yellow to non-yellow dots) were flashed for 150ms. Twelve participants evaluated whether the sentence in (1) was true on each screen and the patterns of accuracy of their responses were analyzed. No difference in accuracy was found as the function of the number of colors of dots, but only as the function of the ratio (in adherence to Weber's law). This indicates that Subtraction was always used for the judgment of (1). Crucially, on the screens with just 2 colors, Selection would be computationally less costly (it would involve less steps than Selection as shown in Table 1) and thus more accurate.

Table 1. Steps involved in Selection as opposed to Subtraction on two-color screens.

Subtraction (irrespective of no. of colors)	*Selection two colors*
1. Estimate the total.	1. Estimate the target set.
2. Estimate the target set.	2. Estimate the distractor set.
3. Subtract the target set from the total.	3. Compare with the target set.
4. Compare the difference with the target set.	

Yet, even on the two-color condition Subtraction appeared to be used, since the accuracy was not higher than on the multi-color screens, i.e. the verification procedure failed to make use of the automatically obtained information, the cardinality of the two subsets that could be compared directly (Halberda et al. 2006). Thus, Lidz et al. conclude that Subtraction is the default procedure for verifying *most* under time pressure. On the basis of this finding they formulate the Interface Transparency Thesis: "the verification procedures that speakers employ, when evaluating sentences they understand, are biased towards algorithms that directly compute the relations and operations encoded by the relevant logical forms" (Pietroski et al. 2011).[2]

[2] What is crucial when comparing different strategies is evidence that a more advantageous strategy is failed to be used in favor of one that can be directly linked to semantics. Pietroski et al. (2011) "take it as given that speakers use various strategies in various situations. For us, the question is whether available procedures are *neglected*—in circumstances where they could be used to good effect—in favor of a strategy that reflects a candidate logical form for the sentence being evaluated." A strategy may be abandoned in favor of one that is unrelated to a semantic representation, but that cannot be taken as evidence against a particular semantic specification.

3 Most1 and Most2 in Bulgarian and Polish

Bulgarian and Polish have "two" versions of the English majority quantifier *most*. Most1 in both languages has the same proportional reading as the English *most* has, so that (8a) and (9a) are equivalent to (1).

8. (a) Povečeto točki sa žəlti. *Bulgarian*
   Most1 dots are yellow
   '**Most** dots are yellow.'
   (b) Naj-mnogo točki sa žəlti.
   Most2 dots are yellow
   'Yellow dots form the largest subset.'
9. (a) Większość kropek jest żółta. *Polish*
   Most1 dots is yellow
   '**Most** dots are yellow.'
   (b) Najwięcej jest kropek żółtych.
   Most2 is dots yellow
   'Yellow dots form the largest subset.'

Most2 in Bulgarian (8b) and Polish (9b) contains superlative morphology in contrast to Most1 as illustrated in (11). In accordance with the standard meaning of the superlative morpheme (the relative reading), Most2 modifying a noun says that what the noun denotes is the most numerous thing among other things of the same type, in our case, the set of yellow dots is more numerous than any other color set.

Table 2. The morphological make-up of Bulgarian and Polish Most1 and Most2.

Most1	Most2
"more than half"	*"largest subset"*
Bulgarian	
po-veče-to *er+many+the*	naj-mnogo **est**+many
Polish	
więk-sz-ość *many+er*+nominalizer	naj-więc-ej **est**+many+er

I predicted that Most1, being equivalent to the English most, should be compatible with the Subtraction strategy. Thus, the number of color sets was expected to not affect the accuracy of judgments with Most1 (it should only be affected by the ratio of yellow to non-yellow dots). Since the semantics of Most2 can be specified as in (10), which I call Stepwise Selection, I expected to find both an effect of ratio and of number of colors in contrast to Most1.

10. Stepwise Selection strategy
|Dot(x) & Yellow(x)| > |Dot(x) & Red(x)|, &
|Dot(x) & Yellow (x)| > |Dot(x) & Blue(x)|, &
|Dot(x) & Yellow (x)| > |Dot(x) & Green(x)|, & …

Both of the predictions were met. The results of the Experiment 1 (on Bulgarian) and of the Experiment 2 (on Polish) contain exactly the same main effects in the two conditions.

3.1 Experiments 1 and 2: Materials and methods

I conducted two on-line visual-display verification studies designed along the lines of the experiment of Lidz et al. (2011). A group of 39 native speakers of Bulgarian participated in Experiment 1 and 20 native speakers of Polish participated in Experiment 2. The Polish experiment is reported in Tomaszewicz (2011).

The procedure was identical in both experiments. The participants evaluated the truth of the sentences in (8-9) by pressing Yes or No buttons while viewing displays of arrays of colored dots on a black background, flashed on a computer screen for 200ms. I manipulated the ratio of the yellow target to the rest (1:2, 2:3, 5:6, i.e. 3 levels of the ratio variable) and the number of color sets (1, 2 or 3 other distractor colors, i.e. 3 levels of the distractor variable). The numbers of colors in each bin are presented in Table 5 in the Appendix.

As the schema in Fig. 8 in the Appendix shows, 360 displays were presented in 2 blocks (180 for Most1 and 180 Most2, half of each requiring a yes response and half a no response). Participants had 380ms to indicate their response by a button press. The experiment was performed using Presentation® software (Version 14.2, www.neurobs.com).

3.2 Experiments 1 and 2: Results

For Most1 accuracy rates were significantly affected only by ratio, and not by number of color sets (Table 3, rows (a),(c)). For Most2 accuracy rates were significantly affected both by ratio and by number of color sets (Table 3, rows (b),(d)). I analyzed each quantifier with a 3x3x2 Repeated Measures ANOVA crossing the 3 levels of the ratio variable, 3 levels of distractor, and the truth/falsity of screens:

Table 3. Accuracy rates.

			ratio				color sets			
			1:2	2:3	5:6		2	3	4	
(a)	Bg	Most1 (*povečeto*)	**.858**	**.778**	**.643**	p<.001	.764	.748	.767	p.=.321
(b)		Most2 (*najmnogo*)	**.827**	**.742**	**.617**	p<.001	**.807**	**.731**	**.648**	p<.001

(c)	Pl	Most1 (*większość*)	**.871**	**.785**	**.673**	p<.001	.797	.763	.769	p.=.215
(d)		Most2 (*najwięcej*)	**.866**	**.76**	**.63**	p<.001	**.801**	**.767**	**.688**	p<.001

The accuracy rates with Most1 in Bulgarian and Polish are significantly affected only by ratio[3] and not by number of color sets. These results are the same as for the English *most* in Lidz et al. (2011) and are entirely consistent with the prediction that Most1 is verified by Subtraction. The graphs in Fig. 2 and Fig. 3 clearly show the lack of a main effect of number (Bulgarian: F(2, 76) = 1.153, p = .321; Polish: F(1.47, 27.98) = 1.637, p = .215[4]).

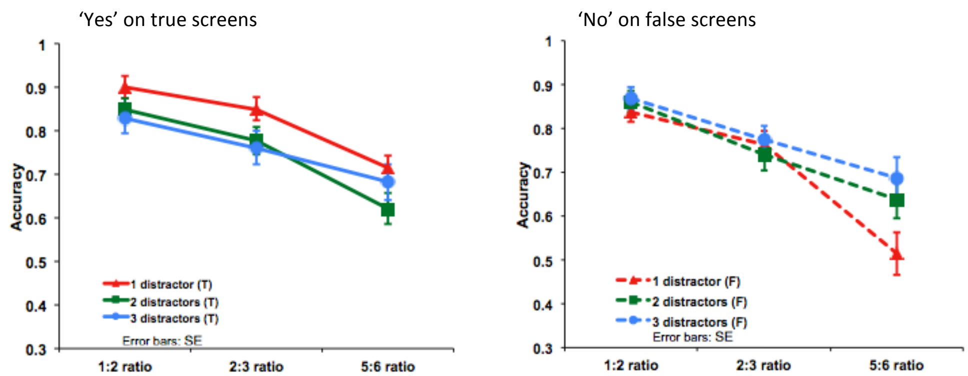

Fig. 2. Most1 in Bulgarian.

'Yes' on true screens

'No' on false screens

[3] Bulgarian: F(2, 76) = 171.791, p < .001, Polish: F(2, 38) = 76.072, p < .001. Post hoc tests using the Bonferroni correction revealed significant differences (p < .001) between all levels of the ratio variable.

[4] Because of the violations of sphericity (p = .019), we are reading the Greenhouse-Geisser corrected value. Whether or not we use this correction, there is still no significance: F(2, 38) = 1.64, p = .208.

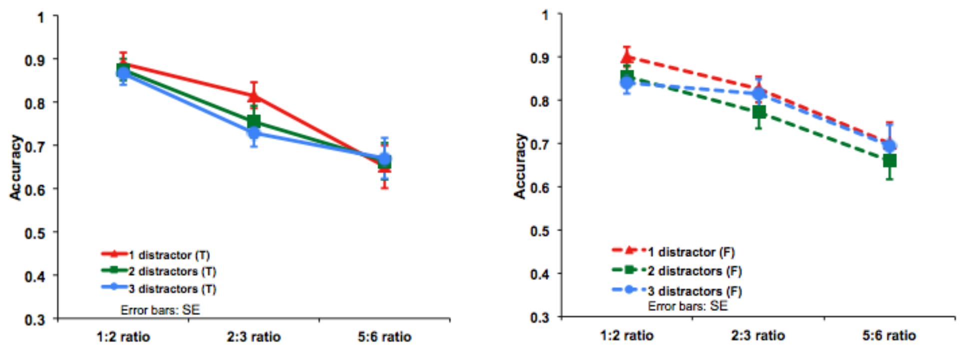

Fig. 3. Most1 in Polish.

The results for Most2 are entirely compatible with the view that it is verified by Selection. In both Bulgarian (Fig. 4) and Polish (Fig. 5) the accuracy rates are significantly affected both by ratio (Bulgarian: F(2, 76) = 182.449, p < .001, Polish: F(2, 38) = 124.77, p < .001) and number of color sets (Bulgarian: F(2, 76) = 72.612, p < .001, Polish: F(2, 38) = 17.34, p < .001).[5]

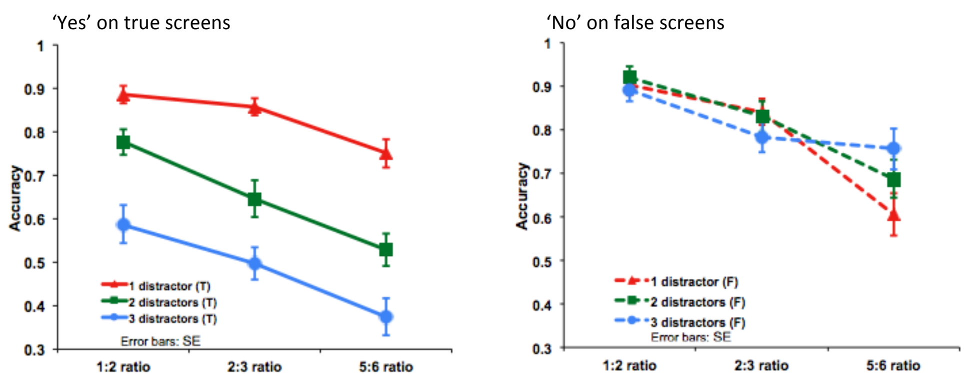

Fig. 4. Most2 in Bulgarian.

'Yes' on true screens 'No' on false screens

[5] Pair-wise comparisons for the main effect of ratio and the main in effect of distractor in Bulgarian (using a Bonferroni correction) revealed significant differences (p < .001) between all levels. For Polish the differences between all levels of the ratio variable were significant (p < .001). The differences between 1-3 and 2-3 distractors were significant (p < .001 and p = .001 respectively), while the difference between 1-2 distractors was not (p = .316). Note that the Polish sample (N=20) is much smaller than the Bulgarian sample (N=39).

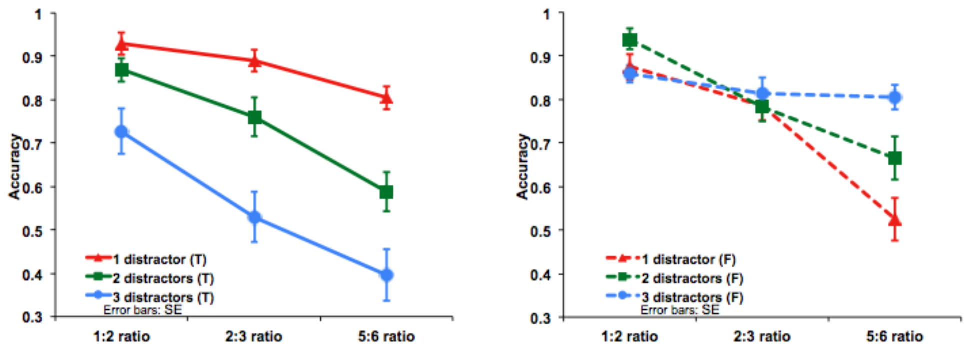

Fig. 5. Most2 in Polish.

It is also evident in the graphs in Fig. 5 and Fig. 6 that the accuracy with Most2 is affected by the truth/falsity of screens. The present design does not allow us to determine the reason for this, however, with Selection correct estimation of both the target set and each color set is expected to be affected by a higher number of factors than Subtraction.

Crucially, the significant effect of number of colors in addition to the effect of ratio indicate that both the yellow set and the other color sets are selected for the verification of Most2 in conformity with its semantics.[6]

Importantly, on screens with 2 color sets (identical for both quantifiers) both Bulgarian and Polish participants were significantly less accurate and slower confirming the truth of Most1 than of Most2. This indicates that Subtraction continues to be used with Most1 and Selection with Most2 even on the condition, where switching between the two procedures would provide more accurate results.

Participants could have used whichever strategy is computationally less costly/more accurate under time pressure, since both strategies are otherwise used by the speakers of Bulgarian and Polish. If the semantic representation guides verification, then with Most2 the non-yellow set should be selected directly – the accuracy should be greater than with Most1 where the non-yellow set is computed (cf. Lidz et al. 2011), which is exactly what we find on true screens.

[6] Note that successful selection and comparison of 3-4 color sets in 200ms is not inconsistent with the findings of Halberda et al. (2006). The three set limit is on the automatically obtained information without a stimulus that creates expectations and directs attention to some specific aspect of the display. The superlative morphology clearly contributes an expectation that multiple sets should be compared.

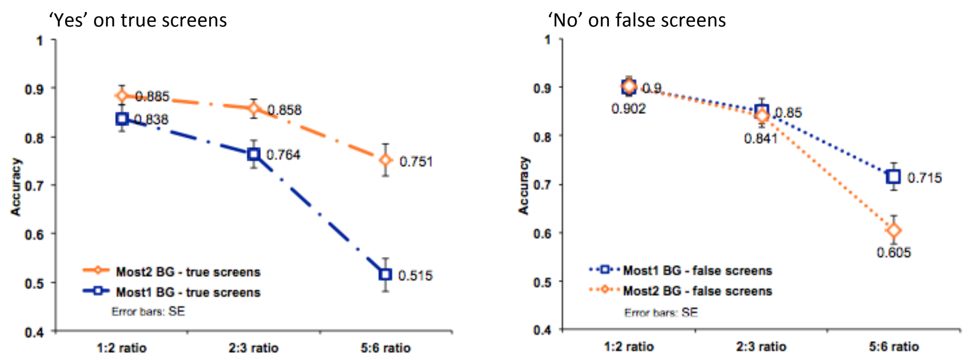

Fig. 6. Two color condition: Most1 vs. Most2 in Bulgarian.

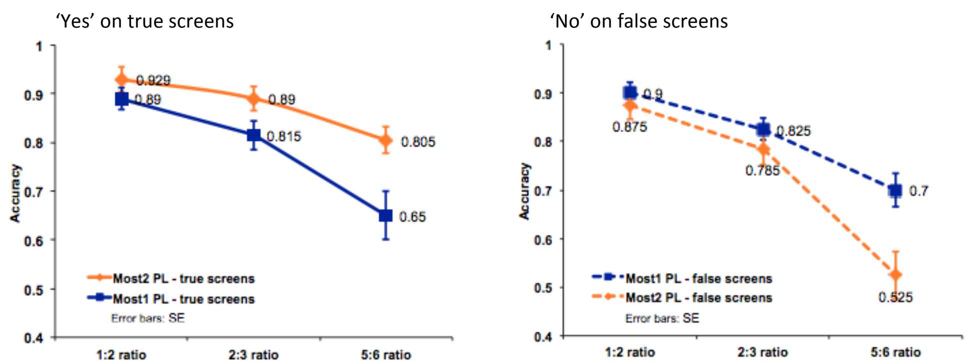

Fig. 7. Two color condition: Most1 vs. Most2 in Polish.

Both Bulgarian and Polish participants were significantly better with Most2 than Most1 on true screens (Bulgarian: ($F(1, 38) = 32.970$, $p < .001$, Polish: $F(1, 19) = 10.49$, $p = .004$). On false screens Most1 is significantly better than Most2 (Bulgarian: ($F(1, 38) = 4.892$, $p = .033$, Polish: $F(1, 19) = 11.122$, $p =.003$).

Notably, the two languages also behave exactly the same with respect to the reaction times. The accuracy is higher despite faster RTs and lower despite slower RTs (Table 4). On true screens Most2 is faster (Bulgarian: $F(1, 38) = .587$, $p = .448$, Polish: $F(1, 19) = 5.173$, $p = .035$). On false screens Most1 is faster (Bulgarian: $F(1, 38) = 9.884$, $p = .003$, Polish: $F(1, 19) = .351$, $p = .561$). See Table 6 in the Appendix for mean RTs. The RT data shows that it is not the case that people are more prone to errors as they make judgments faster. Instead, we can see that the procedure with Most2 on true screens is easier (faster, more accurate judgments) which is expected if the two color sets are selected directly. On false screens Most1 is judged faster and more accurately, which does not seem to follow from Subtraction vs. Selection difference. However, the correct disconfirmation probably involves more factors that cannot be identified on the present design.

Crucially, the accuracy patterns together with RTs consistent in both languages indicate that participants do not switch to the more advantageous strategy, e.g. they don't use Selection to more accurately confirm the truth of Most1. This is the more interesting given the findings of Halberda et al. (2006) that the cardinality of two color sets is automatically computed. Yet the semantics of Most1 apparently precludes the use of this automatically available information.

Different behavior with each quantifier on the very same screens indicates that participants do not switch between the procedures and that the way those procedures differ is specified by the semantics. Computation for both Most1 and Most2 involves the comparison between the yellow and the non-yellow set. The components provided by the visual system are exactly the same: yellow set, non-yellow set, superset. However, the algorithms must be different. To verify Most2 one has to (i) estimate target, (ii) estimate competitor, (iii) compare. To verify Most1 one needs to (i) estimate target, (ii) estimate total, (iii) subtract target from total. The lexical meaning of the functional morphemes that build up Most1 and Most2 and their logical syntax are interfacing with the visual system during the verification process.

4 Conclusions

In conclusion, our experiments indicate that semantics provides a direct set of instructions to the visual cognition processes, and that these instructions are followed even when computationally more advantageous strategies are available.

We have met the prediction that Bulgarian and Polish proportional majority quantifier Most1, just like English *most*, is verified using Subtraction strategy (we found a main effect of ratio and no effect of number of colors). The superlative/relative majority quantifier Most2 requires the Stepwise Selection strategy (as evidenced by the effect of ratio together with the effect of number of colors)[7]. Importantly, in a within-subject design the same group of participants behaves differently depending on the quantifier. The overall patters of accuracy are exactly the same in Bulgarian and Polish.

[7] As one of the reviewers observes, my evidence for the different verification processes for Most1 and Most2 is based on the use of the ANS representation of magnitude for the comparisons required by the semantics. If the superlative Most2 incurs a larger processing cost, it would be interesting to see if we find evidence for it also in experiments where counting is not precluded. Note, however, we cannot just "switch off" ANS, e.g. the effects of ratio-dependency characteristic of ANS are present also with judgments involving Arabic numerals,s although the quantities evoked by Arabic numerals may be more precise than those evoked by sets of dots (Dehaene 1997).

On two color screens (where Most1 and Most2 are either both true or both false) the verification procedure depends on the lexical item used. The patterns of accuracy for Most1 and Most2 were conspicuously different (but had the same direction in both Bulgarian and Polish) indicating that computationally Most1 and Most2 are different.

My results confirm and extend the findings of Pietroski et al. (2008) and Lidz et al. (2011) and indicate that semantics provides inviolable instructions to visual cognition processes.

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Appendix:

Table 5. The numbers of dots in each bin.

Most1 - total number of screens: 180

no. of screens			ratio	dis-trac-tors	no. of yellow dots	no. of non-yellow dots	total no. of dots
30	10	true	1:2	**1**	**8 - 12**	**4 - 6**	**12 - 18**
	10			2	8 - 12	4 - 6	12 - 18
	10			3	8 - 12	4 - 6	12 - 18
30	10	true	2:3	**1**	**8 - 12**	**5 - 8**	**13 - 20**
	10			2	8 - 12	5 - 8	13 - 20
	10			3	8 - 12	5 - 8	13 - 20
30	10	true	5:6	**1**	**8 - 12**	**7 - 10**	**15 - 22**
	10			2	8 - 12	7 - 10	15 - 22
	10			3	8 - 12	7 - 10	15 - 22
30	10	false	1:2	**1**	**5 - 9**	**10 - 18**	**15 - 27**
	10			2	5 - 9	10 - 18	15 - 27
	10			3	5 - 9	10 - 18	15 - 27
30	10	false	2:3	**1**	**5 - 9**	**8 - 14**	**13 - 23**
	10			2	5 - 9	8 - 14	13 - 23
	10			3	5 - 9	8 - 14	13 - 23
30	10	false	5:6	**1**	**5 - 9**	**6 - 11**	**11 - 20**
	10			2	5 - 9	6 - 11	11 - 20
	10			3	5 - 9	6 - 11	11 - 20

Most2 - total number of screens: 180

no. of screens			ratio	dis-trac-tors	no. of yellow dots	no. of dots in closest competitor	total no. of dots
30	10	true	1:2	**1**	**8 - 12**	**4 - 6**	**12 - 18**
	10			2	8 - 12	4 - 6	13 - 23
	10			3	8 - 12	4 - 6	14 - 27
30	10	true	2:3	**1**	**8 - 12**	**5 - 8**	**13 - 20**
	10			2	8 - 12	5 - 8	15 - 27
	10			3	8 - 12	5 - 8	16 - 33
30	10	true	5:6	**1**	**8 - 12**	**7 - 10**	**15 - 22**
	10			2	8 - 12	7 - 10	19 - 31
	10			3	8 - 12	7 - 10	22 - 29
30	10	false	1:2	**1**	**5 - 9**	**10 - 18**	**15 - 27**
	10			2	5 - 9	10 - 18	18 - 35
	10			3	5 - 9	10 - 18	19 - 42
30	10	false	2:3	**1**	**5 - 9**	**8 - 14**	**13 - 23**
	10			2	5 - 9	8 - 14	16 - 31
	10			3	5 - 9	8 - 14	17 - 38
30	10	false	5:6	**1**	**5 - 9**	**6 - 11**	**11 - 20**
	10			2	5 - 9	6 - 11	14 - 28
	10			3	5 - 9	6 - 11	15 - 32

Table 6. Reaction Times (RTs, in tenth of millisecond).

		Most2		Most1	
		true screens	false screens	true screens	false screens
1:2 ratio	BG	8784	9475	9066	9114
	PL	8434	9922	8978	9706
2:3 ratio	BG	`9724	10316	9411	9423
	PL	8797	10498	9892	9789
5:6 ratio	BG	9884	10793	10461	9730
	PL	9569	10204	10217	10660
		Most2 slower on false screens, BG: p = .002, PL: p <.001		Most1: no sig. difference between true and false screens	
		Most2 faster on true screens: BG: p = .45 (ratio*quantifier p = .027), PL: p <.001 Most2 slower on false screens: BG: p = .003, PL: p = .56 (ratio*quantifier p = .003, ratio p = .065)			

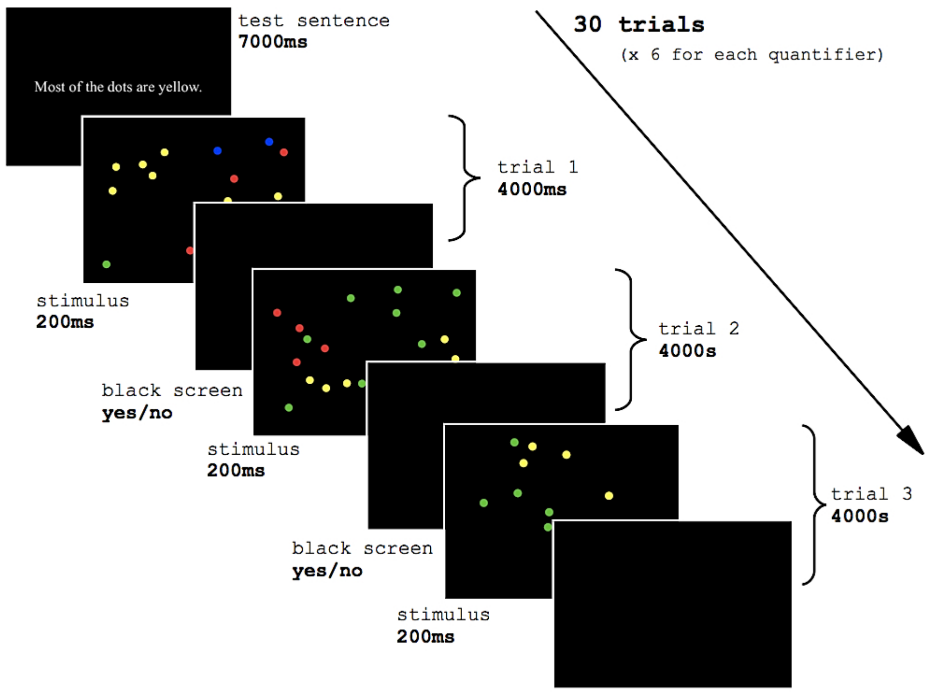

Fig. 8. A schema of the experimental procedure.