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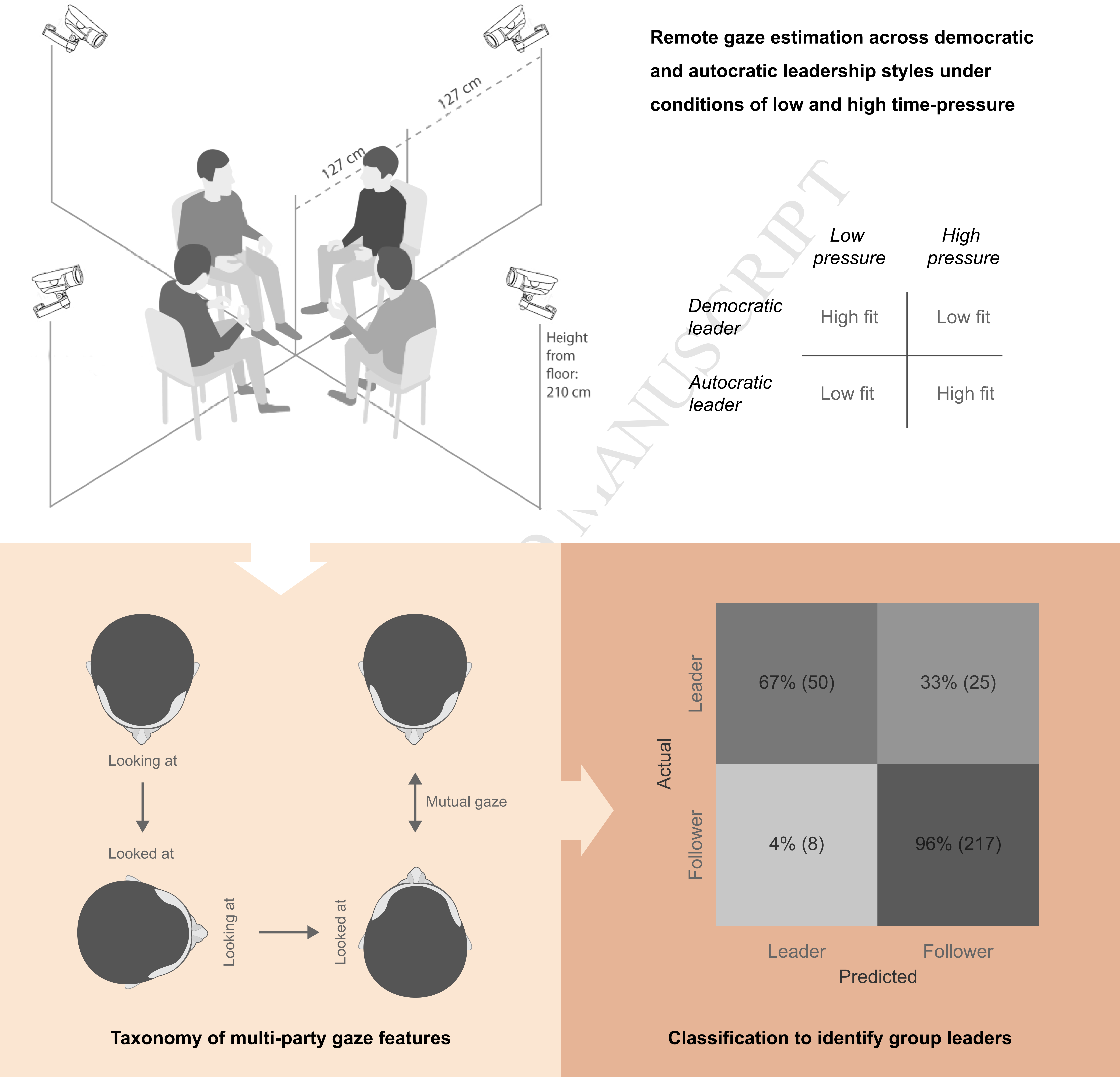
Remote gaze estimation across democratic and autocratic leadership styles under conditions of low and high time-pressure
127 cm
127 cm
Height from floor: 210 cm
Low pressure
High pressure
Democratic leader
High fit
Low fit
Autocratic leader
Low fit
High fit
Looking at
Looked at
Mutual gaze
Looking at
Looked at
Taxonomy of multi-party gaze features
Actual
Leader
Follower
67% (50)
33% (25)
4% (8)
96% (217)
Leader
Follower
Predicted
Classification to identify group leaders

TRACKING THE LEADER: GAZE BEHAVIOUR IN GROUP INTERACTIONS

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Summary

Can social gaze behaviour reveal the leader during real-world group interactions? To answer this question, we developed a novel tripartite approach combining *i*) computer vision methods for remote gaze estimation, *ii*) a detailed taxonomy to encode the implicit semantics of multi-party gaze features, and *iii*) machine learning methods to establish dependencies between leadership and visual behaviours. We found that social gaze behaviour distinctively identified group leaders. Crucially, the relationship between leadership and gaze behaviour generalized across democratic and autocratic leadership styles under conditions of low and high time-pressure, suggesting that gaze can serve as a *general marker of leadership*. These findings provide the first direct evidence that group visual patterns can reveal leadership across different social behaviours and validate a new promising method for monitoring natural group interactions.

Introduction

It is commonly believed that leadership is reflected in gaze behaviour. Stereotypical thinking links leadership to prolonged gazing towards leaders (Hall et al., 2005) and longer mutual gazing in response to interactions initiated by leaders (Carney et al., 2005). However, evidence for an actual relationship between leadership and social gaze behaviours is limited. To date, investigations on the influence of leadership on gaze behaviour have focused on computer-based paradigms that do not provide any opportunity for social interaction (Capozzi and Ristic, 2018; Koski et al., 2015; Risko et al., 2016). The aim of the present study was to develop a novel approach to investigate how leadership shapes gaze dynamics during real-world human group interactions.

Authentic social situations are complex and highly dynamic (Foulsham et al., 2010). What is more, unlike computer-based paradigms, they involve the potential for social interaction and reciprocity. When looking at a representation of a social stimulus (e.g., images of people), individuals need not worry about what their own gaze might be communicating to the stimulus. When looking at real people, in contrast, the eyes not only collect information (encoding function), but also communicate information to others (signalling function; Risko et al., 2016). This dual function of gaze yields an interdependency among multi-agent gaze patterns, which traditional computer-based paradigms, be they static or dynamic scene-viewing tasks, arguably fail to capture (Laidlaw et al., 2011).

Despite a growing understanding of the necessity of studying social cognitive processes in interactive (Schilbach et al., 2013) and complex settings (Frank and Richardson, 2010), little is known about the influence of leadership on gaze-based interactions in unconstrained group interactions. Older studies report that, in dyadic interactions, attribution of power increases as the proportion of looking while speaking increases (Dovidio and Ellyson, 1982; Ellyson et al., 1981; Exline et al., 1975). However, the evidence is inconclusive as to whether gazing decoupled from speaking time identifies leaders (Hall et al., 2005). Moreover, it remains unclear whether the same dynamics constraining dyads also constrain group interactions.

A major reason for the lack of studies investigating group gaze-based interactions is the difficulty of simultaneously tracking transient variations in multi-party gaze features to capture the implicit semantics of social gaze behaviours. In the attempt to overcome these limitations, in this study, we developed a novel tripartite approach combining *i*) computer vision methods for remote gaze-tracking, *ii*) a detailed taxonomy to encode the implicit semantics of multi-party gaze features, and *iii*) advance machine learning methods to establish dependencies between leadership and visual behaviours during unconstrained group interactions involving four people simultaneously. The basic idea for establishing a relationship between social gaze behaviour and leadership was to conceptualize multi-party gaze features as *patterns* and to treat the analysis as a *pattern classification problem*: can a classifier applied to the visual behaviour pattern of real people interacting in small groups reveal the leader? This is the first question we addressed in the study described here. The second question is whether the relationship between gaze behaviour and leadership generalizes across leadership styles and situational conditions – in other words, whether gaze behaviour can serve as *a general marker* of leadership.

Drawing on ideas from social psychology (Chemers, 2014; Foels et al., 2000; Livi et al., 2008; Northouse, 2016), we analysed gaze-based interaction dynamics in four leadership settings resulting from the orthogonal manipulation of leadership style (i.e., Democratic vs. Autocratic) and situational condition (i.e., Low time-pressure vs. High time-pressure). Democratic leadership is expected to be more effective under situational conditions of low time-pressure, whereas autocratic leaderships is expected to be more effective under situational conditions of high time-pressure (Fiedler, 2006; Pierro et al., 2003). The orthogonal manipulation of leadership styles and situational conditions resulted in two high-fit conditions (Democratic - Low time-pressure, Autocratic - High time-pressure) and two low-fit conditions (Democratic - High time-pressure, Autocratic - Low time-pressure) (Figure 1 A; see also SI and Figure S1 for group composition and manipulation checks). Each group, composed of one designated leader and three followers, was assigned a survival task to solve within a limited time (see Figure 1 B for the experimental setting). First, using a method for automatically estimating the Visual Focus of Attention (VFOA; Ba and Odobez, 2006; Beyan et al., 2016; Gatica-Perez, 2009; Stiefelhagen et al., 1999), we determined 'who looked at whom'. Then, we established a detailed taxonomy of multi-party gaze behaviours and, combining the VFOA of individual group-members, reconstructed the gaze-based interaction dynamics. Next, we probed the actual association between leadership and gaze patterns by asking whether a pattern classification algorithm could discriminate leaders and followers among the group-members. After finding evidence for leadership classification, we finally tested whether the classifier was able to generalize across leadership styles, situational conditions, and time.

Results

Extraction of the Visual Focus of Attention (VFoA)

First, using a method for automatically estimating the Visual Focus of Attention (VFOA) (Beyan et al., 2016), we determined 'who looked at whom'. To do so, we recorded the visual behaviour of 16 groups composed of four previously unacquainted individuals over a period of maximum 30 minutes (mean = 23 minutes, range = 12-30). Individuals were sitting on four equidistant chairs (Figure 1 B.1). The visual behaviour of each individual was simultaneously captured by four multi-view streaming cameras (1280x1024 pixels resolution, 20 frame per second frame rate) (Figure 1 B.2). Additionally, a standard camera (440x1080 pixels resolution, and 25 frame per second frame rate) was used to capture the whole scene. An automated extraction technique was used to estimate the frame-by-frame VFOA of each participant (Beyan et al., 2016). The performance of the SVM classifiers used to model the individual VFOAs yielded an average of 72% detection rate (see "Visual Focus of Attention" in Transparent Methods).

Reconstruction of group interaction dynamics

Having determined the VFOA of each participant, we proceeded to reconstruct the gaze-based interaction dynamics by combining the VFOA of individual group-members. To this aim, we derived a detailed taxonomy of multi-party gaze on the basis of the three broad social dimensions classically used in the study of social gaze behaviour (Capozzi and Ristic, 2018; Emery, 2000; Jording et al., 2018; Kleinke, 1986; Pfeiffer et al., 2013), here labelled Participation, Prestige, and Mutual engagement (see Pierro et al., 2003). Participation refers to the amount of time that each individual looks at others and indicates the individual involvement in interactive dynamics (Ellyson and Dovidio, 1985). Prestige refers to the amount of time that each individual is looked at by others and indicates the extent to which one is referred to during an interaction (Feinman et al., 1992). Mutual engagement refers to the amount of time that each individual looks at someone while looked back and indicates the individual engagement in cooperative behaviours (Foddy, 1978). Within these dimensions, we extracted eight multi-party gaze features to capture comprehensively gaze behaviour during group interactions (Table 1; see also Data S1 for gaze behaviour data).

Leader classification by group visual behaviour

To establish a dependency between visual behaviour and leadership, we next trained a linear Support Vector Machine (SVM) to discriminate leaders vs. followers on the extracted multi-party gaze features. Classification performance was computed as the resulting average of a leave-one-subject-out cross-validation scheme (Koul et al., 2018).

With a cross-validated accuracy of 89%, classification performance was well above the .50 chance level (95% CI = .85, .92; Kappa = .68; Sensitivity = .86; Specificity = .90; F1 = .75; $p < .001$). Figure 2 shows the corresponding confusion matrix.

To investigate which features were more effective for the classification task, we next computed F-scores (see “Leader classification analysis” in Transparent Methods). F-score provides a measure of how well a single feature at a time can discriminate between different classes. The higher the F-score, the greater the ability of a feature to discriminate between leaders and followers. Table 2 provides an overall view of the discriminative power of each visual feature.

Overall, F-scores suggest that leaders looked less at others and, conversely, were looked at more as compared with followers. Also, leaders were involved in and caused more episodes of mutual engagement, relative to followers. The time taken by another group member to respond to the initiation of mutual engagement was also less for leader-initiated episodes compared to follower-initiated episodes.

Generalization across leadership styles, situational conditions, and time

To provide direct evidence that the relationship between leadership and visual behaviour generalizes across leadership styles and situational conditions, we next applied Multivariate Cross-Classification (MVCC) analysis to our data (Kaplan et al., 2015). In MVCC, a classifier is trained on one set of data and then tested with another set. If the two data sets share the same patterns, then learning should transfer from the training to the testing set (Kaplan et al., 2015; Kriegeskorte, 2011).

Following this logic, we first applied MVCC analysis to test generalization across leadership styles. We trained a linear SVM to discriminate leaders based on gaze patterns recorded during group interactions with a designated democratic leader, and then tested it on group-interactions with a designated autocratic leader. With an accuracy of 88%, cross-classification performance was well above the .50 chance level (95% CI = .82, .93; Kappa = .66; Sensitivity = .81; Specificity = .90; F1 = .73; $p < .001$). Train-autocratic and test-democratic led to a similar cross-classification accuracy of 90% (95% CI = .84, .95; Kappa = .72; Sensitivity = .89; Specificity = .91; F1 = .78; $p < .001$).

With a similar logic, we applied MVCC to test generalization across situational conditions. We trained a linear SVM on gaze patterns recorded under high fit situational conditions (i.e., democratic leaders working in a low time-pressure condition and autocratic leaders working in a high time-pressure condition), and then tested it on group interactions under low fit situational conditions and vice-versa. Cross-classification performance was once again well above the .50 chance level, reaching 94% and 85% for train-high fit and test-low fit (95% CI = .89, .97; Kappa = .83; Sensitivity = .92; Specificity = .94; F1 = .87; $p < .001$) and train-low fit and test-high fit (95% CI = .78, .91;

Kappa = .54; Sensitivity = .82; Specificity = .86; F1 = .63; $p < .001$), respectively. Collectively, these data show that multi-party visual behaviour supports identification of group leaders across leadership styles (i.e., democratic, autocratic) and situational fit conditions (i.e., high fit, low fit).

Finally, we applied MVCC to test the temporal stability of leadership-related gaze dynamics, that is, whether similar gaze patterns identify leaders over time. To do so, we trained a linear SVM to discriminate leaders based on gaze patterns recorded during the first part of the group task (first half of the video-segments), and then tested it on gaze patterns from the second part of the group task (second half of the video-segments). With an accuracy of 91%, cross-classification performance was well above the .50 chance level (95% CI = .86, .95; Kappa = 0.76; Sensitivity = 0.90; Specificity = 0.92; F1 = .81; $p < .001$). Training on the second part and testing on the first part led to a similar cross-classification accuracy of 89% (95% CI = .83, .94; Kappa = .68; Sensitivity = .92; Specificity = .89; F1 = .74; $p < .001$). These results indicate that leadership-related gaze patterns generalized over time.

Discussion

The study of visual behaviour as a nonverbal index of leadership has received attention both within evolutionary perspectives seeking out the ancestral foundations of the human propensity to organize into social structures (van Vugt, 2014), as well as within social neurocognitive perspectives aiming at describing the neural and cognitive processes that enable such structures (Koski et al., 2015). The joint efforts of these disciplines have so far mainly focused on the conditions that predict who will emerge as leader in a particular situation and on the nonverbal cues that signal or predict leadership effectiveness – a computational problem often referred to as 'leader index' (Grabo et al., 2017). Albeit important, this approach leaves unaddressed a related but distinct 'leader marker' problem: Can the semantics of group visual behaviour reveal the leader among group members?

To address this problem, in the present study, we developed a novel approach combining computer vision methods, a detailed taxonomy of social gaze behaviours, and machine learning methods for pattern classification. We found that social gaze behaviour distinctively identified group leaders. Furthermore, leadership identification generalized across different leadership styles and situational conditions. Intriguingly, the features that contributed to classification spanned all the three dimensions of social visual behaviour: participation, prestige, and mutual engagement. The association of ‘prestige’ to leadership – leaders being looked at more compared to followers – is consistent with previous findings from computer-based studies. For example, studies investigating gaze allocation in video clips found that people perceived as leaders were fixated more often and for a longer total time compared to people perceived as non-leaders (Foulsham et al., 2010; Gerpott et al., 2018). Could this be because leaders tend to speak more than non-leaders? To address this possibility, we performed an additional MVCC analysis training a linear SVM to discriminate leaders based on gaze patterns recorded during the video-segments in which the leader spoke the most, and then tested it on the video-segments in which a follower spoke the most. Cross-classification results confirmed that speaking time was not the factor driving leader identification (see Supplemental Information).

A novel finding of our study is that leaders looked less to others as compared to followers. We propose that this distinctive visual behaviour of leaders may reflect the signalling function of gaze in authentic social situations (Dovidio and Ellyson, 1982; Kalma et al., 1993). That is, thinking their gaze was being monitored by followers, leaders may have implemented a sort of ‘gaze-based impression management’ (Mattan et al., 2017). Similarly, one could hypothesize that followers’ recurrent looks toward leaders and promptness to respond to mutual engagement episodes initiated by leaders betrayed a communicative concern, i.e., communicate their interest in leaders’ opinions. These hypotheses could be tested by manipulating participants’ beliefs about whether or not their own gaze is viewed by others. To the extent that the visual behaviour of group-members reflects gaze-based impression management, one would expect the reported patterns to disappear when people believe that they are not seen by others.

To our knowledge, this is the first study that attempts to provide a full characterization of the relationship between leadership and social gaze behaviour during natural group interactions. The novel method utilized in the current study demonstrates that gaze-based group behaviours distinctively identified leaders during natural group interactions. Leaders were looked at more, looked less at others, and elicited more mutual gaze. This pattern was observed over time regardless of leadership style and situational condition, suggesting that gaze can serve as *a general marker of leadership*. Together with previous findings on body movements (Badino et al., 2014; Chang et al., 2017; D'Ausilio et al., 2012) and paralinguistic behaviours (Gatica-Perez, 2009; Hall et al., 2005; Schmid Mast, 2002), these results demonstrate the significance of non-verbal cues for leadership identification. We expect that future empirical and modelling studies will investigate whether and how different (and possibly correlated) non-verbal features contribute to leader classification. In addition, we anticipate that these findings will inspire new research questions and real-world applications spanning a variety of domains, from business management (Beyan et al., 2018, 2016) to surveillance and politics (Bazzani et al., 2012).

Limitations of the study

In the present study, designated leaders were assigned to groups. It will be important for future studies to investigate whether and to what extent the current findings generalize to emergent leadership (e.g., Jiang et al., 2015). In contrast to designated leaders, emergent leaders gain status and respect through engagement with the group and its task. We would expect that, under these conditions, a temporal generalization method using cross-classification over multiple time windows (King and Dehaene, 2014) may identify different gaze-based interaction dynamics depending on the stage of the interaction. The same approach may also reveal how leadership is distributed among group members across interaction stages.

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Author contributions

Study design: FC, AP, and CBecchio, with the contribution of SL and VM. Assessment of individual dispositions: FC, with the contribution of AP and SL. Data acquisition: FC. Visual Focus of Attention: CBeyan and VM. Classification analyses: FC and AK, with the contribution of CBeyan. Manipulation checks: FC, with the contribution of AP and SL. Data interpretation: all Authors. Manuscript preparation: FC and CBecchio, with the contribution of JR and APB; all Authors revised and approved the final version of the manuscript.

Declaration of interests

The Authors report no competing interests.

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FIGURE TITLES AND LEGENDS

Figure 1. Study design and experimental setting. Panel A: Study design, manipulation of leadership style and situational condition. Panel B: Schematic reproduction of the experimental setting (drawing not to scale). Participants seated on four equidistant chairs (1), while four individual video-cameras were recording the upper part of their bodies (2).

Figure 2. Confusion matrix for the Leaders vs. Followers classification (full dataset, N = 300). Darker shading denotes higher percentages. The actual number of observations is shown in parentheses.

MAIN TABLES AND LEGENDS

Table 1. Gaze behaviour taxonomy: Description, operationalization, and social dimensions of visual features

MULTI-PARTY GAZE FEATURE	OPERATIONALIZATION	INDEXED ON	DIMENSION
Looking at	Video-frames in which each individual looked at another member while not looked back	Total video-frames	*Participation*
Looked at	Video-frames in which each individual was looked at while not looking back	Total video-frames	
Looked at_multiple	Video-frames in which each individual was looked at by two[a] members simultaneously, while not looking back at any of them	Total video-frames	*Prestige*
Looked at_Ratio	Ratio between 'Looked at' and 'Looking at'	NA	
Mutual gaze	Video-frames in which each individual was looking at someone while simultaneously being looked back	Total video-frames	
Mutual gaze_multiple	Video-frames in which each individual was looked at by two[a] members simultaneously, while looking back at one of them	Total video-frames	*Mutual engagement*
Mutual gaze initiation	Frequency of mutual engagement episodes initiated	Total mutual engagement episodes in each video	

Mutual gaze response time	Video-frames between the initiation of a mutual engagement episode and the reaction of the looked at person	Total video-frames

[a] NOTE: For both Looked at_multiple and Mutual gaze_multiple, the number of video-frames in which an individual was looked at by three members simultaneously did not result in values different from zero, thus these features were omitted from subsequent analyses.

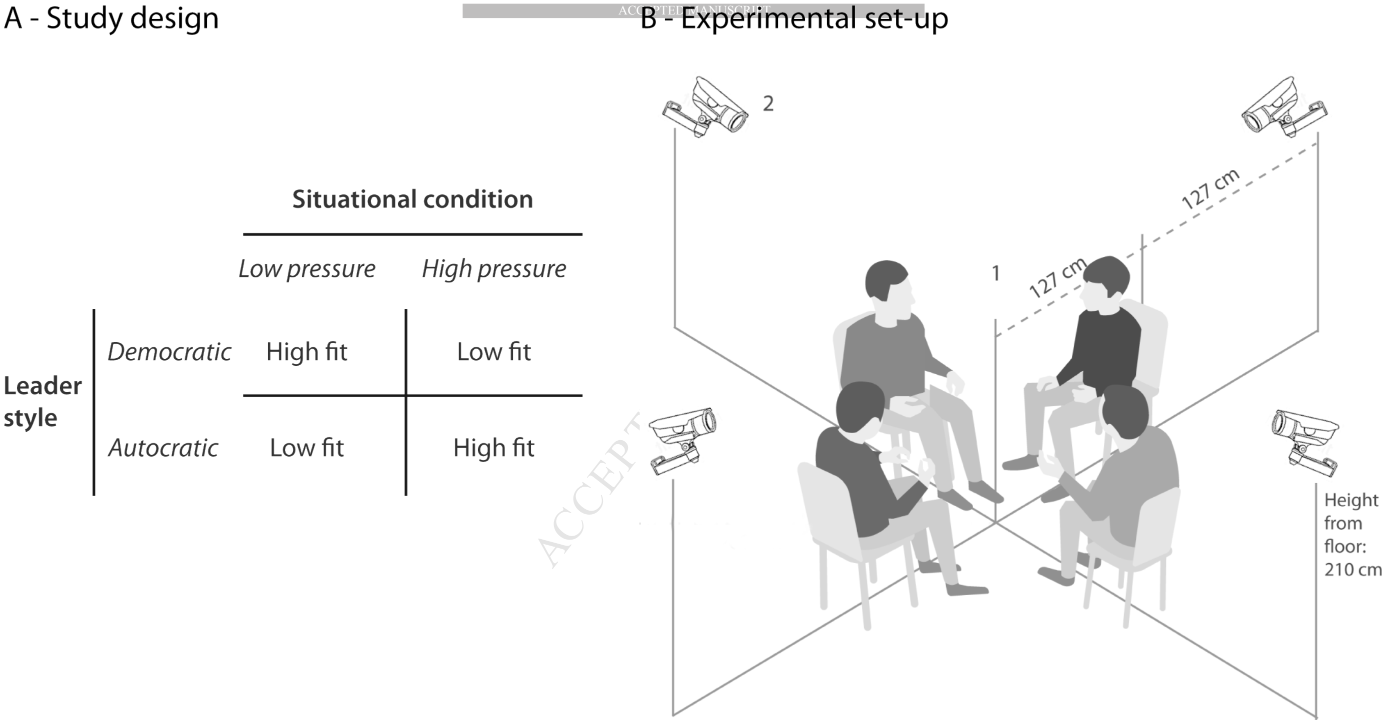
Table 2. F-scores and group means for individual features for discrimination between leaders and followers (full data-set).

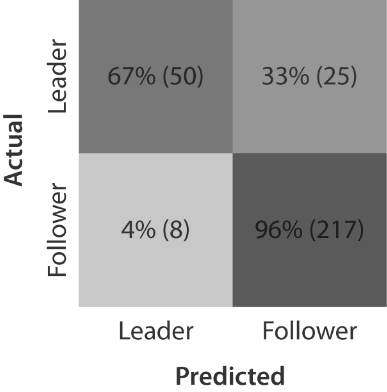
Feature	F-score	Leaders Mean (± SD)	Followers Mean (± SD)
Looking at	1.800	0.36 ± 0.09	0.57 ± 0.13
Looked at_Ratio	1.700	2.43 ± 1.07	0.85 ± 0.53
Looked at	1.300	0.72 ± 0.18	0.43 ± 0.17
Looked at_multiple	1.300	0.28 ± 0.13	0.10 ± 0.08
Mutual gaze	0.780	0.41 ± 0.14	0.24 ± 0.12
Mutual gaze_mutiple	0.450	0.26 ± 0.14	0.15 ± 0.10
Mutual gaze response time	0.350	0.13 ± 0.06	0.19 ± 0.08
Mutual gaze initiation	0.085	0.27 ± 0.08	0.24 ± 0.07

Features are ranked based on F-scores, higher values indicating higher contribution to the classification. The unit of measurement for the means is the proportion of frames in which the visual behaviour occurred (see Table 1).

SUPPLEMENTAL VIDEO, DATA, AND EXCEL TABLE TITLE AND LEGENDS

Data S1. Gaze behaviour data, Related to Table 1


A - Study design
Situational condition
Low pressure
High pressure
Leader style
Democratic
High fit
Low fit
Autocratic
Low fit
High fit
B - Experimental set-up
2
1
127 cm
127 cm
Height from floor: 210 cm


Actual
Leader
Follower
67% (50)
33% (25)
4% (8)
96% (217)
Leader
Follower
Predicted

Highlights

- Leadership shapes gaze dynamics during real-world human group interactions
- Social gaze behaviour distinctively identifies group leaders
- Identification generalizes across leadership styles and situational conditions
- Gaze can serve as a general marker of leadership