Systematic and integrative analysis of large gene lists using DAVID bioinformatics resources

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DAVID bioinformatics resources consists of an integrated biological knowledgebase and analytic tools aimed at systematically extracting biological meaning from large gene/protein lists. This protocol explains how to use DAVID, a high-throughput and integrated data-mining environment, to analyze gene lists derived from high-throughput genomic experiments. The procedure first requires uploading a gene list containing any number of common gene identifiers followed by analysis using one or more text and pathway-mining tools such as gene functional classification, functional annotation chart or clustering and functional annotation table. By following this protocol, investigators are able to gain an in-depth understanding of the biological themes in lists of genes that are enriched in genome-scale studies.

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INTRODUCTION

High-throughput genomic, proteomic and bioinformatics scanning approaches, such as expression microarray, promoter microarray, proteomic data and ChIP-on-CHIPs, provide significant capabilities to study a large variety of biological mechanisms, including associations with diseases. These technologies usually result in a large 'interesting' gene list (ranging in size from hundreds to thousands of genes) involved in studied biological conditions. Data analysis of the large gene lists is a very important downstream task following the above example of high-throughput technologies to understand the biological meaning of the output gene lists. The data analysis of such highly complex and large volume data sets is a challenging task, which requires support from special bioinformatics software packages. In this protocol, we introduce DAVID (the database for annotation, visualization and integrated discovery) bioinformatics resources[1,2], which is able to extract biological features/meaning associated with large gene lists. DAVID is able to handle any type of gene list, no matter which genomic platform or software package generated them.

DAVID, released in 2003 (refs. 2,3), as well as a number of other similar publicly available tools, including, but not limited to, GoMiner[4], GOstat[5], Onto-express[6], GoToolBox[7], FatiGO[8], GFINDer[9], GOBar[10] and GSEA[11] (see **Supplementary Data 1** for a complete list), address various aspects of the challenge of functionally analyzing large gene lists. Although each tool has distinct features and strengths, as reviewed by Khatri *et al.*[12], they all adopt a common core strategy to systematically map a large number of interesting genes in a list to the associated biological annotation (e.g., gene ontology terms), and then statistically highlight the most overrepresented (enriched) biological annotation out of thousands of linked terms and contents. Enrichment analysis is a promising strategy that increases the likelihood for investigators to identify biological processes most pertinent to the biological phenomena under study.

The analysis of large gene lists is indeed more of an exploratory, computational procedure rather than a purely statistical solution. As compared with other similar services, DAVID provides some unique features and capabilities, such as an integrated and expanded back-end annotation database[13], advanced modular enrichment algorithms[14] and powerful exploratory ability in an integrated data-mining environment[1]. Even though users can learn more in-depth information about DAVID algorithms in our original publications[1–3,13–15], we now briefly summarize the rationale regarding the key DAVID modules, as well as the analytic limitations (see **Table 1** for comparisons of DAVID's analytical modules), so that readers may be able to quickly follow the protocol.

Large gene lists ready for functional analysis by DAVID

In this protocol, we use a previously published gene list[16] (**Supplementary Data 2**) as an example to illustrate the results obtained from the various DAVID analytic modules. To obtain this list, freshly isolated peripheral blood mononuclear cells were treated with an HIV envelope protein (gp120) and genome-wide gene expression changes were observed using Affymetrix U95A microarray chips[16]. The aim of the experiment was to investigate cellular responses to viral envelope protein infection, which may help in understanding the mechanisms for HIV replication in resting or suboptimally activated peripheral blood mononuclear cells.

The quality of large gene lists derived from high-throughput biological studies is one of the most important foundations that directly influence the success of the following functional analysis in DAVID. Owing to the complexity of the data-mining situations involved in biological studies, there is no good systematic way, at present, to quantitatively estimate the quality of the gene list ahead of time (i.e., before the gene functional analysis). However, on the basis of real-life data analysis experiences during the past several years, a 'good' gene list may exhibit most, if not all, of the following characteristics:

(1) Contains many important genes (marker genes) as expected for given study (e.g., IL8, CCL4 and TNFSF8 from the example gene list in **Supplementary Data 2**).
(2) Reasonable number of genes ranging from hundreds to thousands (e.g., 100–2,000 genes), not extremely low or high.
(3) Most of the genes significantly pass the statistical threshold for selection (e.g., selecting genes by comparing gene expression between control and experimental cells with *t*-test statistics:

TABLE 1 | Side-by-side comparisons of DAVID's major analytic modules.

	Input user's large gene lists				
DAVID analytic module/tool	**Gene name batch viewer[1]**	**Gene functional classification[14]**	**Functional annotation chart[1,2]**	**Functional annotation clustering[14]**	**Functional annotation table[1,2]**
Brief definition/ explanation	List names of user's genes	Classify user's genes into gene groups	Identify enriched annotation terms associated with user's gene list	Cluster functionally similar terms associated with user's gene list into groups	Query associated terms for all user's genes
Key points	Gene-centric singular exploration	Gene-centric modular analysis	Term-centric singular enrichment analysis (typical enrichment analysis)	Term-centric modular enrichment analysis	Large-scale query
Example question to ask	What are the genes in my list?	What are the major gene families in my list?	Which annotation terms are enriched for my gene list?	Which annotation groups are enriched for my gene list?	What are the associated annotations for each of my genes?
Main functions	Display all gene names in a linear tabular text format Deep links to more information around given gene Search other functionally related genes	Classify functionally related genes into groups 2D view for related gene–term relationship Rank importance of gene groups with enrichment score Highlight annotation terms for gene groups	Identify enriched annotation terms in a linear tabular text format Deep links to more information around terms and associated genes Search other functionally related terms View genes on pathway maps	Cluster functionally related annotations into groups 2D view for related gene–term relationship Rank importance of annotation groups with enrichment score Pool genes for annotation groups	Query selected annotations for given genes
Advantages	Roughly explore genes one by one Quickly check if the expected/important genes are in the list Quickly learn annotation about genes of interests All genes are included in the analysis	Explore genes group by group rather than singular genes one by one Highlight important gene groups by enrichment scores Study functionally related genes and their relationship in a network format Good to catch major biology	Simple format to explore all singular enriched terms	Explore annotations group by group rather than singular terms one by one Highlight important annotation groups by enrichment scores Study functionally related genes and their relationship in a network format Good to focus on major and fine-level biology	Quickly explore all annotations (both enriched and non-enriched ones) for given genes Good for analysis of small number of focused genes Save entire annotation profile of a given gene list in text file ready for other external analysis
Drawbacks	Related genes scattered in the results lose interrelationships during exploration Difficult to judge important genes or nonspecific genes without enrichment calculation	Some genes without strong neighbors will be left out from the analysis	Related/redundant terms scattered in the results Some fine-level biology could be diluted by the redundancy Lack of term–term relationships during analysis	Some enriched terms without strong neighbors will be left out from the analysis	Difficult to explore large gene list No enrichment analysis

fold changes ≥ 2 and P-values ≤ 0.05). Importantly, statistical thresholds do not have to be sacrificed (e.g., fold changes ≥ 1.1 and P-value ≤ 0.2) to reach a comfortable gene size.

(4) Notable portion of up- or downregulated genes are involved in certain interesting biological processes, rather than being randomly spread throughout all possible biological processes.

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(5) A 'good' gene list should consistently contain more enriched biology than that of a random list in the same size range during analysis in DAVID (see **Supplementary Data 3** for detailed discussions).
(6) High reproducibility (e.g., by independent experiments under the same conditions or by leave-one-out statistical test) to generate a similar gene list under the same conditions.
(7) The high quality of the high-throughput data can be confirmed by other independent wet lab tests or experiments.

Some of these points (2, 3, 6 and 7) come from upstream analysis, whereas DAVID may help in examining others (1, 4 and 5).

Moreover, for enrichment analysis, in general, a larger gene list can have higher statistical power resulting in a higher sensitivity (more significant *P*-values) to slightly enriched terms, as well as to more specific terms. Otherwise, the sensitivity is decreased toward largely enriched terms and broader/general terms. Although the size of the gene list influences (in a nonlinear way) the absolute enrichment *P*-values, which makes it difficult to directly compare the absolute enrichment *P*-values across gene lists, the enrichment *P*-values are fairly comparable within the same or same size of gene list. In addition, when different sizes of gene lists are generated from the same data set with different threshold stringencies (within a reasonable range), the absolute enrichment *P*-values may vary from list to list. However, the relative rank/order of the enriched terms may remain fairly stable, which will lead to consistent global conclusions of functional annotations across the different sizes of gene lists derived from the same data set (data not shown). This kind of reproducibility and consistency should be expected using DAVID tools if the underlying high-throughput biological studies are robust.

Interestingly, we found that many gene lists input to DAVID are in the size range of 1–10 genes. The enrichment statistic's power will be very limited in such extreme cases. However, the unique exploratory capability of DAVID could still be very powerful for analyzing such small gene lists. As the analysis is most likely in a very focused and small scope, analysts may take advantage of the unique exploratory capability of DAVID to navigate through all of the well-organized heterogeneous annotation contents around the focused genes regardless of the statistics.

Submission of user's gene identifiers to DAVID

Comprehensively mapping of a user's gene identifiers (gene IDs) to the relevant biological annotation in the DAVID database is an essential foundation for the success of any high-throughput gene functional analysis. Gene IDs and biological annotations are highly redundant within the vast array of public databases. The DAVID knowledgebase[13] was designed to collect and integrate diverse gene identifiers as well as more than 40 well-known publicly available annotation categories (**Supplementary Data 4**), which are then centralized by internal DAVID identifiers in a nonredundant manner. The wide range of biological annotation coverage and the nonredundant integration of gene IDs in the DAVID knowledgebase enables a user's gene ID to be mapped across the entire database, thus providing comprehensive coverage of gene-associated annotation. If a significant portion ($\geq$20%) of input gene IDs fail to be mapped to an internal DAVID ID, a specially designed module, the DAVID Gene ID Conversion Tool[15], will start up to help map such IDs.

Principle of 'gene population background' in enrichment analysis

The principle foundation of enrichment analysis is that if a biological process is abnormal in a given study, the co-functioning genes should have a higher potential (enriched) to be selected as a relevant group by the high-throughput screening technologies. To decide the degree of enrichment, a certain background must be set up to perform the comparison (also see Step 1 in **Table 2**). For example, 10% of the user's genes are kinases versus 1% of the genes in the human genome (this is the gene population background) that are kinases. The enrichment can therefore be quantitatively measured by some common and well-known statistical methods, including χ^2, Fisher's exact test, Binomial probability and Hypergeometric distribution. Thus, a conclusion may be obtained for the particular example, that is, kinases are enriched in the user's study, and therefore have important functions in the study. However, we cannot make such a conclusion with 10% alone, without comparing it with the background information (i.e., 1%).

In this sense, the background is one of the critical factors that impact the conclusion to a certain degree, particularly when two ratios are close. There are many ways to set the backgrounds, e.g., all genome genes; genes on an Affymetrix chip; and a subset of genome genes that the user used in their study. In general, larger backgrounds, e.g., the total genes in the genome as a population background, intend to give more significant *P*-values, as compared with a narrowed-down set of genes as a population background, such as genes existing only on a microarray. Even though there is no gold standard for the population background, a general guideline is to set up the population background as the pool of genes that have a chance to be selected for the studied annotation category in the scope of the users' particular study.

One of the advantages of DAVID is its flexibility of setting different population backgrounds to meet different situations. DAVID has an automatic procedure to 'guess' the background as the global set of genes in the genome on the basis of the user's uploaded gene list. Thus, in a regular situation, users do not have to set up a population background by themselves. We found that it works generally well just because most of the studies analyzed by DAVID are genome-wide or close to genome-wide studies. Moreover, other options are also available for user's choices, including all genes in the studied genome, genes in various microarray chips and most importantly any gene set that users define and upload. The last feature requires significant computational power so that it is rarely found in similar Web-based applications. In summary, various settings and options for population backgrounds can meet the range of needs of general users to those of power users.

DAVID gene name batch viewer

Gene IDs, such as Entrez Gene 3558, typically do not convey biological meaning in and of itself. The gene name batch viewer[1] is able to quickly attach meaning to a list of gene IDs by rapidly translating them into their corresponding gene names (**Fig. 1**, and see slide 4 of **Supplementary Data 5** for more detail). Thus, before proceeding to analysis with other more comprehensive analytic tools, investigators can quickly glance at the gene names to further gain insight about their study and to answer questions such as, 'Does my gene list contain important genes relevant to the study?'. In addition, a set of hyperlinks

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TABLE 2 | Major statistical methods and associated parameters used in DAVID.

Step no.	Module/page	Statistics/parameters	Explanation/definition	How to understand the value
1	Submission of User's Gene IDs	Background genes (or called population genes)	To decide the degree of enrichment, a certain background must be set up to be compared with the user's gene list. For example, 10% of user's genes are kinases versus 1% of genes in human genome (this is population background) are kinases. Thus, the conclusion is obvious in the particular example that the user's study is highly related to kinase. However, 10% itself alone cannot provide such a conclusion without comparing it with the background information	A general guideline is to set up the reference background as the pool of genes that have a chance to be selected for the studied annotation category under the scope of users' particular study Default background is the entire genome-wide genes of the species matching the user's input IDs. Prebuilt backgrounds, such as genes in Affymetrix chips and so on, are available for the user's choice In principle, a larger gene background tends to give smaller *P*-values. As most of the high-throughput studies are, or at least are close to, genome-wide scope, the default background is good for regular cases in general
4	Gene Functional Classification[1,14]	Classification stringency	To control the behavior of DAVID Fuzzy clustering	A general guideline is to choose higher stringency settings for tight, clean and smaller numbers of clusters; otherwise, lower for loose, broader and larger numbers of clusters Default setting is medium Five predefined levels from lowest to highest for user's choices Users may want to play with different stringency for more satisfactory results
		Enrichment score (for each group)	To rank overall importance (enrichment) of gene groups. It is the geometric mean of all the enrichment *P*-values (EASE scores) for each annotation term associated with the gene members in the group. To emphasize that the geometric mean is a relative score instead of an absolute *P*-value, minus log transformation is applied on the average *P*-values	A higher score for a group indicates that the gene members in the group are involved in more important (enriched) terms in a given study; therefore, more attention should go to them Enrichment score of 1.3 is equivalent to non-log scale 0.05. Thus, more attention should be given to groups with scores ≥ 1.3 However, the gene groups with lower scores could be potentially interesting and should be explored as well, if possible
6	Functional Annotation Chart[1,2]	*P*-value (or called EASE score)	To examine the significance of gene–term enrichment with a modified Fisher's exact test (EASE score). For example, 10% of user's genes are kinases versus 1% of genes in human genome (this is population background) are kinases. Thus, the EASE score is <0.05, which suggests that kinases are significantly more enriched than random chance in the study for this particular example	The smaller the *P*-values, the more significant they are Default cutoff is 0.1 Users could set different levels of cutoff through option panel on the top of result page. Owing to the complexity of biological data mining of this type, *P*-values are suggested to be treated as score systems, i.e., suggesting roles rather than decision-making roles. Users themselves should play critical roles in judging 'are the results making sense or not for expected biology'
		Benjamini	To globally correct enrichment *P*-values to control family-wide false discovery rate under certain rate (e.g., ≤ 0.05). It is one of the multiple testing correction techniques (Bonferroni, Benjamini and FDR) provided by DAVID	More terms examined, more conservative the corrections are. As a result, all the *P*-values get larger It is great if the interesting terms have significant *P*-values after the corrections. But as the multiple testing correction techniques are known as conservative approaches, it could hurt the sensitivity of discovery if overemphasizing them. Users' judgment could be critical as discussed in EASE score in Functional Annotation Chart section

(continued)

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TABLE 2 | Major statistical methods and associated parameters used in DAVID (continued).

Step no.	Module/page	Statistics/parameters	Explanation/definition	How to understand the value
		Fold enrichment	To measure the magnitude of enrichment. For example, 10% of user's genes are kinases versus 1% of genes in human genome (this is population background) are kinases. Thus, the fold enrichment is tenfold. Fold enrichment along with EASE score could rank the enriched terms in a more comprehensive way	Fold enrichment 1.5 and above are suggested to be considered as interesting Fold enrichment and EASE score should always be examined side by side. Terms with larger fold enrichments and smaller may be interesting Caution should be taken when big fold enrichments are obtained from a small number of genes (e.g., ≤ 3). This situation often happens to the terms with a few genes (more specific terms) or of smaller size (e.g., <100) of user's input gene list. In this case, the reliability is not as much as those fold enrichment scores obtained from larger numbers of genes
		%	Number of genes involved in given term is divided by the total number of user's input genes, i.e., percentage of user's input gene hitting a given term. For example, 10% of user's genes hit 'kinase activity'	It gives overall idea of gene distributions among the terms The higher percentage does not necessarily have a good EASE score because it also depends on the percentage of background genes as discussed in the EASE score in Functional Annotation Chart section
8	Functional Annotation Clustering[1,14]	Classification stringency	To control the behavior of DAVID Fuzzy clustering	A general guideline is to choose higher stringency setting for tight, clean and smaller numbers of clusters; otherwise, lower for looser, broader and larger numbers of clusters Default setting is medium Five predefined levels from lowest to highest for user's choices Users may want to play with different stringency to obtain more satisfactory results
		Enrichment score (for each group)	To rank overall importance (enrichment) of annotation term groups. It is the geometric mean of all the enrichment *P*-values (EASE scores) of each annotation term in the group. To emphasize that the geometric mean is a relative score instead of an absolute *P*-value, minus log transformation is applied on the average *P*-values	A higher score for a group indicates that annotation term members in the group are playing more important (enriched) roles in given study; therefore, pay more attention toward them Enrichment score 1.3 is equivalent to non-log scale 0.05. Thus, more attention should be given to groups with scores ≥ 1.3 However, the annotation groups with lower scores could be potentially interesting, and should be explored as well if possible
		P-value (or called EASE score) (for individual term members)	To examine the significance of gene–term enrichment with a modified Fisher's exact test (EASE score). This *P*-value is calculated in exactly the same way as in the Functional Annotation Chart section	The explanation is the same as that in Functional Annotation Chart section
		Benjamini	To globally correct enrichment *P*-values of individual term members. The idea and calculations are exactly the same as that in Functional Annotation Chart section	The explanation is the same as that in the Functional Annotation Chart section

are provided for each gene entry, allowing users to further explore additional functional information about each gene.

DAVID gene functional classification

As the analysis proceeds, gene functional classification[14] provides the distinct ability for investigators to explore and view functionally related genes together, as a unit, to concentrate on the larger biological network rather than at the level of an individual gene. In fact, the majority of cofunctioning genes may have diversified names so that genes cannot be simply classified into functional groups according to their names. However, gene functional classification, accomplished with a set of novel fuzzy clustering

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techniques, is able to classify input genes into functionally related gene groups (or classes) on the basis of their annotation term co-occurrence rather than on gene names. Condensing large gene lists into biologically meaningful modules greatly improves one's ability to assimilate large amounts of information and thus switches functional annotation analysis from a gene-centric analysis to a biological module-centric analysis (**Fig. 2**, and see slides 5 and 6 of **Supplementary Data 5** for more details). Taken together with the 'drill-down' function associated with each biological module and visualizations to view the relationships between the many-genes-to-many-terms associations, investigators are able to more comprehensively understand how genes are associated with each other and with the functional annotation.

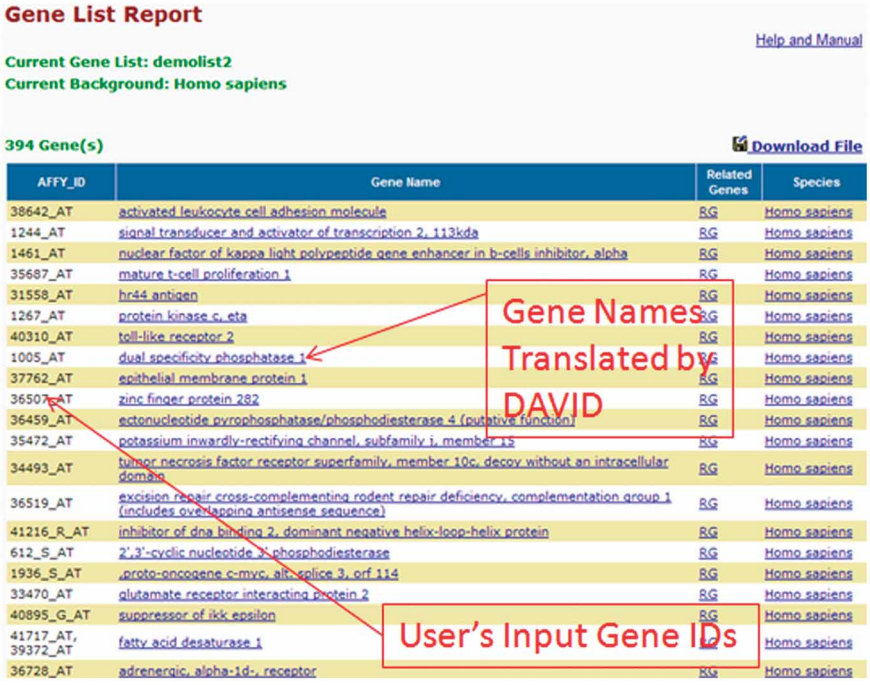

Figure 1 | An example layout of DAVID gene name batch viewer. User's input gene IDs are translated into meaningful and readable gene names. The link on each gene name can lead to more in-depth information.

DAVID functional annotation chart

Functional annotation chart[1–3] provides typical gene–term enrichment (overrepresented) analysis, which is also provided by other similar tools, to identify the most relevant (overrepresented) biological terms associated with a given gene list (**Fig. 3**, and see slide 8 of **Supplementary Data 5** for more detail). Compared with other similar enrichment analysis tools, the notable difference of this function provided by DAVID is its extended annotation coverage[13], increasing from only GO in the original version of DAVID to presently over 40 annotation categories, including GO terms, protein–protein interactions, protein functional domains, disease associations, bio-pathways, sequence features, homology, gene functional summaries, gene tissue expression and literature (**Supplementary Data 4**). The annotation categories can be flexibly included or excluded from the analysis on the basis of a user's choices (see slide 7 of **Supplementary Data 5**). The enhanced annotation coverage alone increases the analytic power by allowing investigators to analyze their genes from many different biological aspects in a single space. In addition, to take full advantage of the well-known KEGG and BioCarta pathways, DAVID pathway viewer, which is accessed by clicking on pathway links within the chart report, can display genes from a user's list on pathway maps to facilitate biological interpretation in a network context (see slide 9 of **Supplementary Data 5**). Finally, the choice of prebuilt or

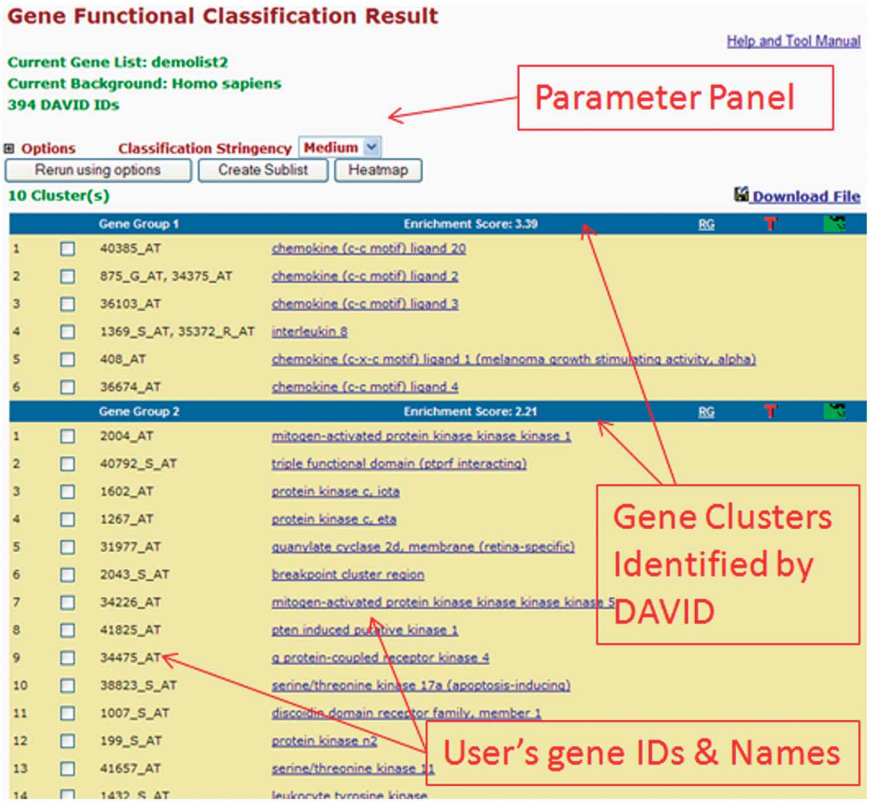

Figure 2 | An example layout of DAVID gene functional classification. User's genes were organized and condensed into several functional groups. The gene members in each group share common biological functions. A set of accessory tools provided for each group will further facilitate the 'drill-down' analysis of biological inter-relationships among the gene members within the same group.

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user-defined gene population backgrounds provides the user with the ability to tailor the enrichment analysis to meet the user's specific analytic situation.

DAVID functional annotation clustering

Functional annotation clustering[14] uses a similar fuzzy clustering concept as functional classification by measuring relationships among the annotation terms on the basis of the degree of their coassociation with genes within the user's list to cluster somewhat heterogeneous, yet highly similar annotation into functional annotation groups (**Fig. 4**, see slide 10 of **Supplementary Data 5** for more detail). This reduces the burden of associating different terms associated with the similar biological process, thus allowing the biological interpretation to be more focused at the 'biological module' level. The 2D view tool is also provided for examining the internal relationships among the clustered terms and genes (see slide 6 of **Supplementary Data 5**). This type of grouping of functional annotation is able to give a more insightful view of the relationships between annotation categories and terms compared with the traditional linear list of enriched terms, as highly related/redundant annotation terms may be dispersed among hundreds, if not thousands, of other terms.

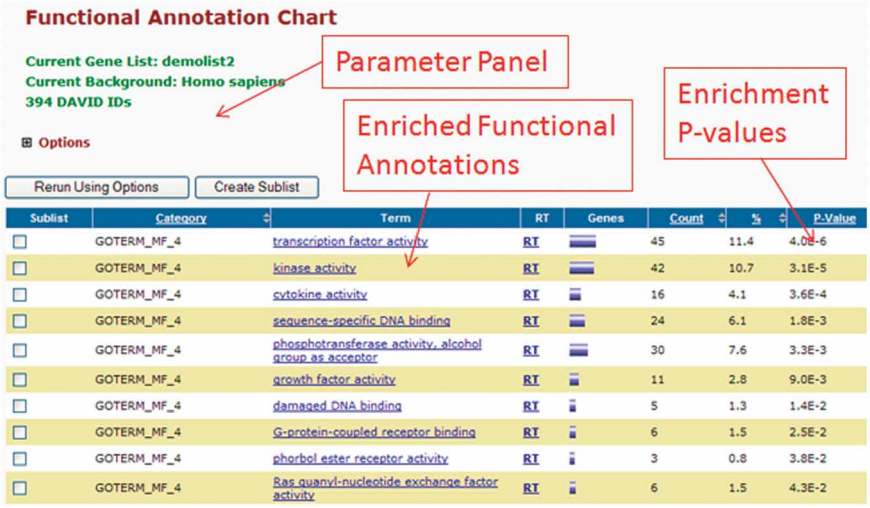

Figure 3 | An example layout of DAVID annotation chart. The enriched functional annotation terms associated with user's gene list are identified and listed according to their enrichment *P*-value by DAVID. The links on the page can lead to various detailed information regarding corresponding items.

DAVID functional annotation table

Functional annotation table[1,2] is a query engine for the DAVID knowledgebase, without statistical calculations (**Fig. 5**, see slide 11 of **Supplementary Data 5** for further details). For a given gene list, the tool can quickly query corresponding annotation for each gene and present them in a table format. Thus, users are able to explore annotation in a gene-by-gene manner. This is a useful analytic module particularly when users want to closely look at the annotation of highly interesting genes.

Summary

Collectively, all of the DAVID analytic modules aim to extract biological meaning from the given gene list from different biological angles with highly consistent and expected results for a given study. Integration of the results from the different analytic modules (**Fig. 6**) will take advantage of the different focus and strength of each module, to make the overall biological picture assembled on the basis of the gene list, more comprehensive and detailed. For a given gene list, DAVID bioinformatics resources is able to help users to (**Fig. 6b**):

- Convert gene IDs from one type to another
- Diagnose and fix problems with gene IDs
- Explore gene names in batch
- Discover enriched functionally related gene groups
- Display relationship of many-genes-to-many-terms on 2D view
- Provide an initial glance of major biological functions associated with gene list
- Identify enriched (overrepresented) annotation terms
- Visualize genes on BioCarta and KEGG pathway maps
- Link gene–disease associations
- Highlight protein functional domains and motifs
- Redirect to related literature
- List interacting proteins
- Cluster redundant and heterozygous annotation terms
- Search other functionally similar genes in genome, but not in list

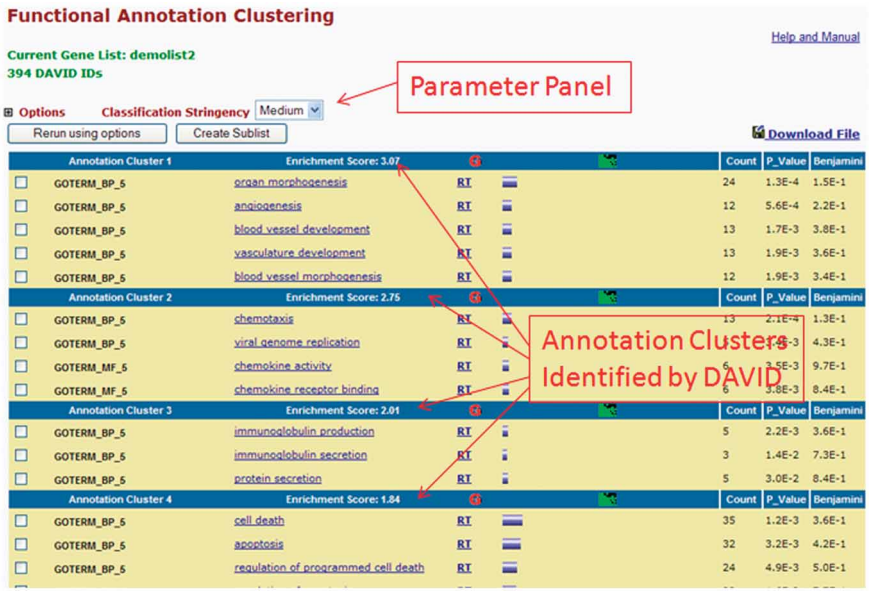

Figure 4 | An example layout of DAVID functional annotation clustering. The similar annotation terms are grouped into clusters so that the user can read through the important terms in the way of block by block instead of individual by individual.

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- Search other annotations functionally similar to one of interest
- Read all annotation contents associated with a gene.

This article will mainly describe the protocol of how to use each DAVID analytic module in a logical, sequential order, as well as how to switch among the analytic modules (**Fig. 6**). The example gene list used in this protocol (also available as demo list 2 on DAVID website) allows new users to quickly test and experience various functions provided by DAVID. The protocol provides a routine analytic flow for new users to begin, as well as the flexibility for experienced users to use, the modules in different combinations to balance the different focuses and strengths of each module to better meet specific analytical questions (**Fig. 6**). Moreover, **Table 2** lists major statistical methods and filtering parameters that may influence the DAVID analysis and result interpretation in certain ways, for users to quickly look up specific statistical topics according to their interests.

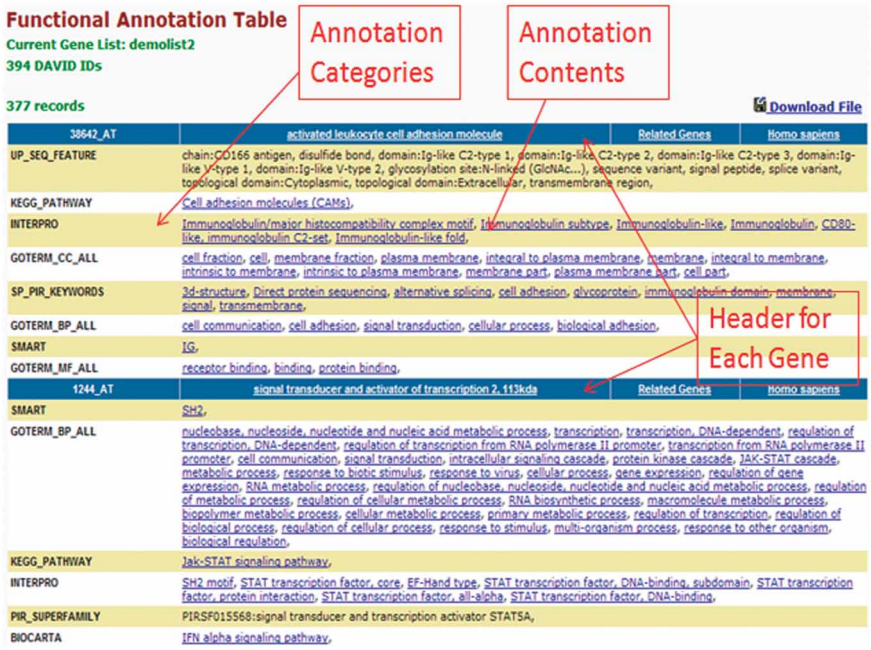

Figure 5 | An example layout of DAVID Annotation Table. Various annotation contents for a given gene are listed in a tabular format. The contents for each gene are separated by the header rows in blue color.

MATERIALS

EQUIPMENT

A computer with high-speed Internet access and a Web browser.

EQUIPMENT SETUP

Hardware requirements and computer configurations DAVID is a Web-based tool designed so that a computer with a standard Web browser using default settings should work well. There is no need for special configuration and installation. Although DAVID was tested with several combinations of Internet browsers and operating systems, MS Internet Explorer or Firefox in a Window XP operating system is recommended to obtain the most satisfactory usability.

Input data A list of gene identifiers is the only required input for all DAVID analytic modules or tools. The gene list may be derived from any type of high-throughput genomic, computational or proteomic study, such as DNA expression microarray, proteomics, CHIP-on-CHIP, SNP array, CHIP-sequence and so on. The format of the gene list to be uploaded is described throughout the website and is either one gene ID per line or a list of comma-delimited gene IDs in one line (**Supplementary Data 6**). DAVID supports most common public gene identifiers[13] (see **Supplementary Data 4**). In addition, after the gene list is submitted to DAVID, all DAVID analytic modules can access the present list from the gene list manager so that there is no need to resubmit the gene list for each DAVID tool.

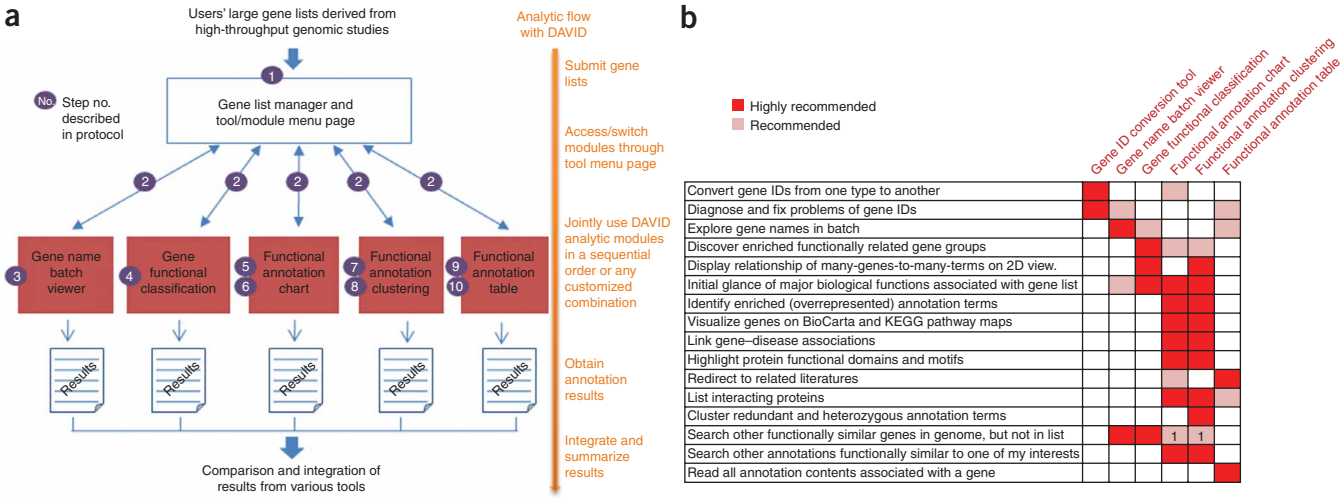

Figure 6 | Analytic tools/modules in DAVID. (**a**) After the user's gene list is submitted to DAVID, the gene list manager may be accessed by all DAVID analytic modules (red boxes) at any time. The circled numbers indicate step numbers described in PROCEDURE to facilitate reading. (**b**) DAVID analytic modules, each having different strengths and focus, can be used independently or jointly. A roadmap to help users to choose some or all DAVID analytic modules for the analysis of large gene lists.

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An example gene list derived from an HIV microarray study[16] is used in this protocol, as well as available as demo_list2 on DAVID website. The HIV microarray study is briefly described in INTRODUCTION. More detail can be found in the original publication[16].

Result download All results derived from DAVID may be explored and visualized on the Web browser. Moreover, all results generated by DAVID can be downloaded in simple flat text formats, thereafter to be edited or plotted by other graphic tools, e.g., MS Excel, for publication purposes as well as for archive purposes.

PROCEDURE

Submission of user's gene IDs to DAVID

1| Submit a gene list to DAVID (**Fig. 7**, and see slide 2 of **Supplementary Data 5** for further details). To do this, go to http://david.abcc.ncifcrf.gov or http://david.niaid.nih.gov and click on 'Start Analysis' on the header. Use the gene list manager panel that appears on the left side of the page (**Fig. 7**) and perform the following steps:

(A) Copy and paste a list of gene IDs into box A or load a text file containing gene IDs to box B (see more details regarding format requirements in EQUIPMENT SETUP, and also see **Supplementary Data 6**).

(B) Select the appropriate gene identifier type for your input gene IDs (see more details of supported ID types in EQUIPMENT SETUP).

(C) Indicate the list to be submitted as a gene list (i.e., genes to be analyzed) or as background genes (i.e., gene population background).

(D) Click the 'Submit List' button.

! CAUTION It takes ~30 s for a typical submission of ~1,000 gene IDs; the progress bar, below the header, will disappear after a successful submission and a gene list name should appear in the list manager box; if ≥20% input gene IDs cannot be recognized, the submission will be redirected to the DAVID Gene ID Conversion Tool[15] for further diagnosis. By default, the background is automatically set up as the genome-wide set of genes for the species that is found to have the majority of genes in the user's input list. However, it is always a good practice to double-check the default, or select a more appropriate prebuilt background through the 'background' tab on top of the list manager.

? TROUBLESHOOTING

2| Access DAVID analytic modules (**Fig. 7**, and see slide 3 of **Supplementary Data 5**) through the tools menu page. The tools main menu is the central page that lists a set of hyperlinks leading to all available analytic modules. Clicking on each link will lead to the corresponding analytic module for analysis of your present gene list, highlighted in the gene list manager.

▲ CRITICAL STEP By clicking on 'Start Analysis' on the header menu, users can always go back to this page at any time, no matter where they are, for choosing or switching to other analysis modules for the present gene list.

Gene name batch viewer

3| Run 'Gene Name Batch Viewer' and explore results (**Fig. 1**, and see slide 4 of **Supplementary Data 5**). To do this, click on the 'Gene Name Batch Viewer'

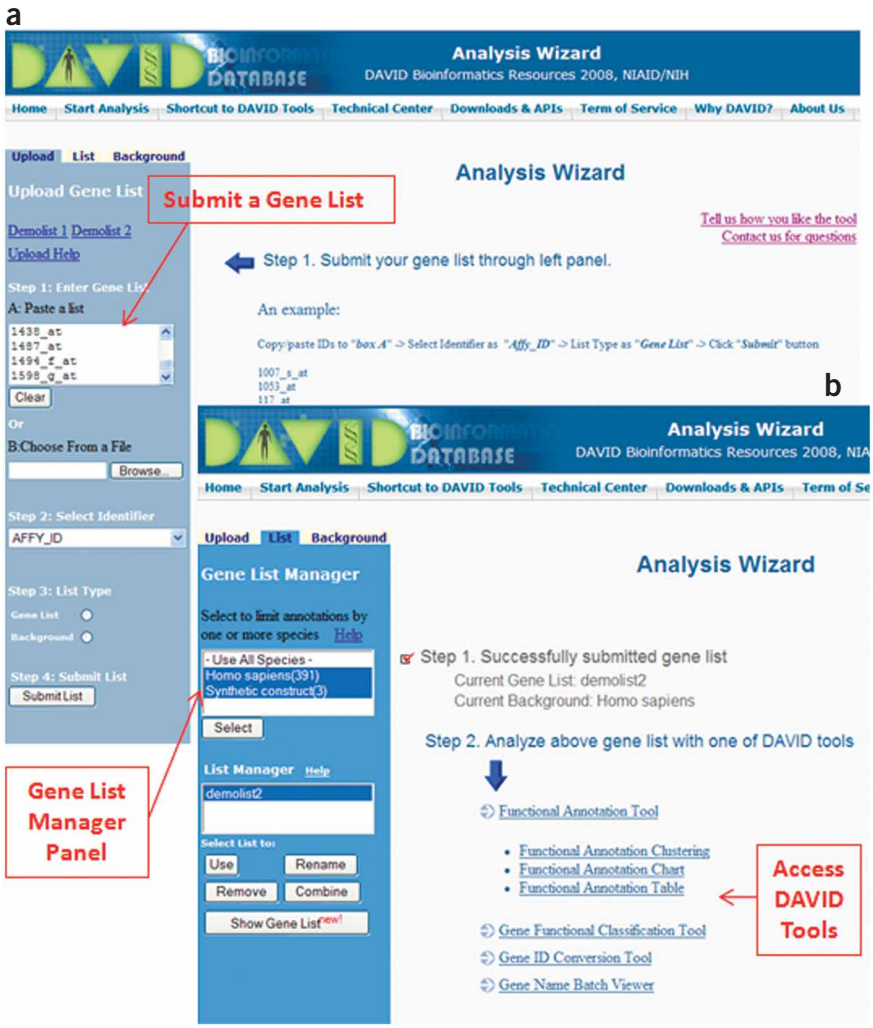

Figure 7 | Submit a gene list to DAVID and access various analytic tools/modules. (**a**) Following the example input format and steps on the left-side uploading panel, a list of genes may be uploaded into DAVID. (**b**) After successfully uploading a gene list(s), a set of analytic modules are available for the analysis of the present gene list highlighted in the gene list manager on the left side. Importantly, users may go to this page at any time by clicking 'Start Analysis' on the header to access any analytic tool of interest.

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link on the tools menu page. All the gene names will be listed by the gene name batch viewer. For a gene of interest, one or all of following options may be conducted

(A) Click on the gene name to link to more detailed information.
(B) Click on 'RG' (related genes) beside the gene name to search for other functionally related genes.
(C) Use the browser's 'Find' function to search for particular items.

? TROUBLESHOOTING

Gene functional classification

4| Run 'Gene Functional Classification' and explore results (**Fig. 2**, and see slide 5 of **Supplementary Data 5**). To do this, return to the tools menu page by clicking on 'Start analysis' on the header. Click on 'Gene Functional Classification Tool' to classify the input gene list into gene groups. For any gene groups of interest, one or all of the following options may be conducted:

(A) Click on the gene name that leads to individual gene reports for in-depth information about the gene.
(B) Click on the red 'T' (term reports) to list associated biology of the gene group.
(C) Click on 'RG' (related genes) to list all genes functionally related to the particular gene group.
(D) Click on the 'green icon' to invoke 2D (gene-to-term) view.
(E) Create a new subgene list for further analysis on a subset of the genes.

! CAUTION The input genes are classified using the default clustering stringency. Users may rerun the classification function leading to optimal results for the particular case by resetting the stringency (high, medium or low) in the options on top of the result page.

▲ CRITICAL STEP 2D view is a Java Applet application that may take awhile to load for the first time; the 2D view Java Applet may require you to accept the online security certificate.

? TROUBLESHOOTING

Functional annotation chart

5| Run 'Functional Annotation Chart' (see slide 7 of **Supplementary Data 5**). To do this, return to the tools menu page by clicking on 'Start Analysis' on the header. Click on 'Functional Annotation Chart' to go the 'Summary Page' of the tool suite. Choose functional annotation categories of your interest (see slide 7 of **Supplementary Data 5**) either by accepting seven default functional annotation categories or by expanding the tree beside each main category (i.e., main accessions, gene ontology and so on) to select or deselect functional annotation categories of your interest. Then click on the 'Functional Annotation Chart' button on the bottom of the page leading to a chart report.

6| Explore the results of the 'Functional Annotation Chart' (**Fig. 3**, and see slide 8 of **Supplementary Data 5**). For an annotation term of interest, one or all of following options may be conducted:

(A) Click on the term name linking to a more detailed description.
(B) Click on 'RT' (related terms) to list other related terms.
(C) Click on the 'blue bar' to list all associated genes.
(D) Click on a pathway name to view genes on the pathway picture.

! CAUTION By default, the order of the annotation terms is based on the EASE (enrichment) score. However, results can also be sorted by different values in the columns. The annotation terms with EASE score ≤ 0.1 are displayed in the results by default. The stringency of this filter (EASE score cutoff) may be set higher or lower through the options provided at the top of the report page to include more or less of the annotation terms.

? TROUBLESHOOTING

Functional annotation clustering

7| Run 'Functional Annotation Clustering' (see slide 10 of **Supplementary Data 5**). To do this, return to the tools menu page by clicking on 'Start Analysis' on the header. Click on 'Functional Annotation Clustering' to go to the 'Summary Page' of the tool suite. Select annotation categories as described in Step 5, then click on the 'Functional Annotation Clustering' button on the bottom of the page.

8| Explore the results of 'Functional Annotation Clustering' (**Fig. 4**, and see slide 10 of **Supplementary Data 5**). For an annotation term cluster of interest, one or all of following options may be conducted:

(A) Click on the term name linking to a more detailed description.
(B) Click on 'RT' (related terms) to list other related terms.
(C) Click on the 'blue bar' to list all associated genes of corresponding individual term.
(D) Click on the red 'G' to list all associated genes of all terms within the cluster.
(E) Click on the 'green icon' to display the 2D (gene-to-term) view for all genes and terms within the cluster.

! CAUTION The annotation terms are clustered using the default clustering stringency. Users may rerun the classification

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function leading to optimal results for the particular case by resetting the stringency (high, medium or low) in the options on top of the result page.
? TROUBLESHOOTING

Functional annotation table

9| Run 'Functional Annotation Table' (see slide 11 of **Supplementary Data 5**). To do this, return to the tools menu page by clicking on 'Start Analysis' on the header. Click on 'Functional Annotation Table' to go the 'Summary Page' of the tool suite. Select annotation categories as described in Step 5, then click on 'Functional Annotation Table' button on the bottom of the page.

10| Explore the results of 'Functional Annotation Table' (**Fig. 5,** and see slide 11 of **Supplementary Data 5**). For a gene of your interest, the following options may be conducted:

(A) Click on annotation terms for a detailed description.

(B) Click on 'Related Genes' to search functionally related genes.

! CAUTION As the output is too large to be displayed by Internet browsers, only top 500 records are shown on the result page. However, full results are available to be downloaded as a tab-delimited text file through the download link on top of the result page.
? TROUBLESHOOTING

● TIMING

The total analysis time varies, ranging from several minutes to hours, and is dependent on the analytical questions being addressed, the number of genes in the list being analyzed and the familiarity with the tools. It is not uncommon to make several visits to focus on different questions regarding a gene list of interest. Indeed, computational time is only a small portion of the total time, whereas exploring, interpreting and re-exploring both within DAVID and external to DAVID tends to dominate most of the time. We used a PC computer with the Windows XP operating system, 2-GB memory, 2.0 GHz CPU and 1-Mbps Internet connection for the data analysis of a gene list consisting of ~400 Affymetrix IDs (**Supplementary Data 2**) derived from an HIV study[16] (presented in ANTICIPATED RESULTS). During the analysis course, for regular functional calls, each result was typically returned in ~10 s. For the most computationally intensive functions, such as gene functional classification, results were typically returned within ~30 s; otherwise, never longer than 1 min.

? TROUBLESHOOTING

Troubleshooting advice can be found in **Table 3**.

TABLE 3 | Troubleshooting table.

Step	Problem	Possible reason	Solution
1	Gene ID submission is stuck and I got the message, "You are either not sure which identifier type your list contains, or less than 80% of your list has mapped to your chosen identifier type. Please use the Gene Conversion Tool to determine the identifier type"	User knows the correct gene ID types, but selected wrong one that did not match the actual input IDs	Go back to resubmit with correct selection of gene ID type or move forward with DAVID Gene ID Conversion tool to determine the potential gene ID type
		User does not know the correct gene ID type corresponding to their gene list	Submission panel in DAVID offers a special ID type, called 'Not sure'. Gene ID submission will be redirected to the DAVID Gene ID Conversion tool, which has a mechanism to scan the entire ID system in DAVID to help you to determine the potential ID type(s) of your genes
		There is more than one type of gene ID in the user's list	DAVID Gene ID Conversion Tool can help you determine the gene ID types and translate them to one single type
		User's gene IDs may contain a version number	Remove the version number, as DAVID will not recognize them
		≥20% of your gene IDs belong to low quality or retired IDs	DAVID Gene ID Conversion Tool may help to identify the problem IDs. The user should consider removing them from the gene list or move forward to analysis, ignoring the problem

(continued)

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TABLE 3 | Troubleshooting table (continued)

Step	Problem	Possible reason	Solution
1 and 3	The gene number that DAVID recognizes does not match the number in my gene list	Repeated IDs in user's list	DAVID ID submission will automatically remove redundancy
		Particular ID(s) mapped to many different genes	DAVID ID Conversion Tool could help to identify the problem IDs. User should consider removing the 'bad' ID(s) from the gene list
		User's input gene IDs are gene symbols	Gene symbol is not species specific, so one symbol may be mapped to many homologous genes across different species. You can define particular species matching your study, after the gene symbols are submitted, in the gene list manager
3, 4, 6, 8 and 10	Result page is blank or empty	30-min timeout	If your Web browser is inactive for more than 30 min, DAVID will clean up all information (your gene list and so on) on the server side. Thus, you have to restart your analysis by resubmitting your gene list
		The size of the gene list is too small	Enrichment or clustering algorithms are based on the survey between input genes against background genes. Thus, a reasonable size (e.g., >30) of input genes is required. Otherwise, certain algorithms will not work properly
		The cutoff or stringency options are too high	Lower down the thresholds accordingly
		Wrong background selected	Background is automatically set up as the genome-wide set of genes corresponding to the species for the majority of genes in the gene list. Sometimes, the system may not choose the appropriate species. User may check and correct the appropriate background through the Gene List Manager
		Small or minor species	Some small species may have very little annotation for the genes. There is nothing that can be done about this situation. Alternatively, you could map the genes to the homologous genes in a better-annotated species
4, 8	2D view is not displayed	Network certificate	Please accept it by clicking on 'Accept'. Basically, you are telling your browser to trust the DAVID application
		Java plug-in is not enabled	By default, most browsers should have the Java plug-in enabled. In case yours is not, please turn it on through Internet Options
NA	Service is too slow	Slow computer and/or Internet speed	Make sure that you have a reasonably good computer and Internet speed. See recommendations in MATERIALS
		Gene list is too large (>3,000)	Please be patient
		DAVID server is overwhelmed	The DAVID service may sometimes be slow due to too many large, simultaneous requests. We have monitoring programs to autodetect and fix the situation in a short time period. If the situation is not resolved in a reasonable amount of time, please report the problem to the DAVID team through the contact provided on the DAVID website

NA, not applicable.

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ANTICIPATED RESULTS

We use submission of the example gene list (~400 genes derived from an HIV microarray study[16]) to DAVID to illustrate the results obtained from various DAVID analytic modules. More detailed information and the availability regarding the gene list can be found in the Materials and Introduction sections of this protocol. Moreover, **Supplementary Data 5** provides screen shots of each major step of the following analysis.

Submission of user's gene IDs to DAVID

A successful submission of the gene list to DAVID is shown in **Figure 7** (also see slides 2 and 3 of **Supplementary Data 5**). Users should see the progress bar under the header move through submission and disappear upon completion of the submission. The gene list manager panel on the left side thereafter displays the list name (e.g., Upload_list_1) and corresponding species information (*Homo sapiens* (391)). The number (i.e., 391) appended after the species information is the number of genes that are recognized by DAVID. A set of hyperlinks on the right-side page lists the analytic modules available in the DAVID analytic pipeline. Users may follow the order of the pipeline to conduct analysis or jointly use analytic modules in varying combinations to meet the user's specific needs (**Fig. 6**). Most importantly, the page serves as a central page (**Fig. 7**) for users to choose analytic modules. Users may go back to this page at any time by clicking the 'Start Analysis' button on the header to switch back and forth among analytic modules as needed.

Gene name batch viewer

The corresponding gene names of input gene IDs are displayed as shown in **Figure 1** and slide 4 of **Supplementary Data 5**. Users may explore the gene names to examine whether there are any interesting study or marker genes in the list. Many immune-related genes, containing names like 'interleukin', 'chemokine', 'kinase' and 'tumor necrosis factor' can be found in the example list, which are consistent with that reported in the publicaton[16]. A set of hyperlinks provided for each gene can further lead to more detailed information about a given gene. In addition, by clicking on the 'RG' (related genes) search function beside a gene name, e.g., 'interleukin 8', all other functionally related chemokine genes (e.g., *cxcl 1*, *2*, *3*, *4*, *20*) will be listed so that users will be able to see other functionally similar genes in the list based on the bait gene.

Gene functional classification

The tool classified the example gene list (~400 genes) into ten functional groups in an easily readable tabular format. An example output is illustrated in **Figure 2** as well as in slide 5 of **Supplementary Data 5**. Gene groups (with significant enrichment scores ≥ 1), such as cytokines/chemokines (group 1: 3.39), kinases (group 2: 2.21), clathrin membrane fusion genes (group 3: 1.86), transcription factors (group 6: 1.39) and so on, can easily be identified. All of these gene groups are highly relevant to an HIV study and are therefore expected biological results[16]. Organizing the large gene list into gene groups allows investigators to quickly focus on the overall major common biology associated with a gene group rather than one gene at a time, thereby avoiding dilution of focus during the analysis due to too many single genes. Furthermore, the '2D View' function associated with each group is able to display all related terms and genes in detail in one picture, to examine their interrelationships. For example, for the kinase group (group 2), a user who is not familiar with kinases may explore the terms of kinase activity, transferase activity, ATP-binding, nucleotide binding, protein metabolism, tyrosine specificity, serine/threonine specificity, regulation of G protein signaling, signal transduction and so on in one view at the same time (slide 6 of **Supplementary Data 5**). Therefore, we can quickly learn the biology for the kinase group, with the above-mentioned related terms in a single view and also identify the fine differences among them. For example, there are two G-protein-coupled receptor kinases, three protein tyrosine kinases and six kinases involved in cell surface receptor-linked signal transduction among the 23 kinases within the group. The fine details may be very important for pinpointing the key biology associated with a study.

Functional annotation chart

Over 500 enriched (overrepresented) biological terms were reported (**Fig. 3**, and slide 8 of **Supplementary Data 5**). Many of them are highly immune related, such as response to pathogenic bacteria, chemokine activity, cell migration, clathrin-coated vesicle membrane, kinase activity, RNA polymerase II transcription factor activity, cell communication. This is consistent with observations identified earlier by the other analytic modules, as well as meeting the expectation for the HIV study[16]. The report offers a lot of redundant details regarding the enriched biology associated with the gene list, which certainly helps the interpretation of the biology, but also may dilute the focus. Moreover, a set of hyperlinks provided for each term will lead to more details about each term, such as in-depth description, associated genes, other related terms, directed acyclic graph (DAG) of GO and so on. Notably, the pathway viewer module offers visualization of users' genes on enriched pathways. For example, 'IL-10 Anti-inflammatory Signaling Pathway' was reported in the output. We can observe that IL10 was activated as an upstream immune regulator and was then further regulated by HO-1. As a result, the IL1/TNFa/IL6 complex was activated leading to further downstream inflammatory responses (**Fig. 8**, and slide 9 of **Supplementary Data 5**). Thus, the interrelationship of input genes was examined on the pathway in a network context.

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Functional annotation clustering

The tool condensed the input gene list into smaller, much more organized biological annotation modules in a similar format (**Fig. 4**, and see slide 10 of **Supplementary Data 5**) as that of gene annotation clustering, but in a term-centric manner. Similarly, it allows investigators to focus on the annotation group level by quickly organizing many redundant/similar/hierarchical terms within the group. Annotation clusters, such as immune response, transcriptional regulation, chemokine activity, cytokine activity, kinase acitivity, signaling transduction, cell death and so on, could be found on the top of the output as expected for this study[16]. The highly organized and simplified annotation results allow users to quickly focus on the major biology at an annotation cluster level instead of trying to derive the same conclusions by putting together pieces that are scattered throughout a list of hundreds of terms in a typical term-enrichment analysis. In addition, the 'G' (genes) link provided for each cluster can comprehensively pool all related genes from different terms within the cluster. For example, each of the seven terms within cluster 2 (inflammatory response cluster) associates with both overlapping as well as differing genes. Therefore, a pooled gene list brought together by cluster 2 regarding inflammatory response may be much more comprehensive, compared with the genes selected from one or a few individual terms.

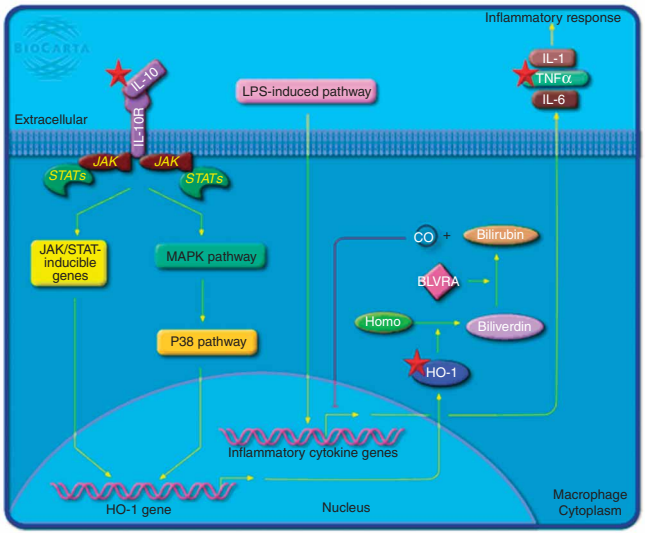

Figure 8 | Pathway map viewer. The red star indicates the associations between pathway genes and the user's input genes. Following the pathway flow, IL10 was activated as an upstream immune stimulator. Then, the middle stream gene, HO-1, was involved. IL-1/INFa/IL-6, as downstream regulator, was finally activated. Thus, the user's genes may be analyzed in a network context.

Note: Supplementary information is available via the HTML version of this article.

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